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EFFECTS OF ADDED SOFTENING
AGENTS UPON THE BEHAVIOR
OF COLD RECYCLED ASPHALT
MIXTURES

Akio Iida

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Interim Report

EFFECTS OF ADDED SOFTENING AGENTS UPON THE BEHAVIOR
OF COLD RECYCLED ASPHALT MIXTURES

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

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

October 1, 1980

Project: C-36-21D

File: 2-8-4

Attached is an Interim Report "Effects of Added Softening Agents Upon the Behavior of Cold Recycled Asphalt Mixtures" which is part of the HPR Research Project titled "An Investigation of Recycling Bituminous Pavements". The report was authored by Mr. Akio Iida, a Graduate Instructor in Research on our staff under the direction of Professors W. H. Goetz and L. E. Wood.

This report presents the results of a study that dealt with the long-term behavior of recycled mixtures especially when the recycling is done cold. The long-term properties of laboratory specimens prepared with different softening agents were evaluated by means of a creep test. A design procedure for cold recycled mixtures is proposed which recommends that blending curves be developed and that a creep test be used to determine mixture properties over a period of time.

This report is offered as fulfillment of Task I of the Project and is submitted for review and acceptance by ISHC and FHWA. The remaining task is currently active.

Respectfully submitted,

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Interim Report

THE EFFECTS OF ADDED SOFTENING AGENTS UPON THE
BEHAVIOR OF COLD RECYCLED ASPHALT MIXTURES

by

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Joint Highway Research Project

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The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data represented 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.

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HIGHLIGHT SUMMARY

Recycling is the technique of reusing paving mixtures deteriorated through weathering and use. The fundamental concept of recycling paving mixtures lies in softening old mixtures by the addition of softening agents so that properties of the bituminous materials in the old mixtures are restored.

The technique has recently become widely utilized in a practical manner, but unsolved problems still remain. One of them is the long-term behavior of recycled mixtures especially when the recycling is done cold. Upon the application of a softening agent to the old asphalt mixture, a blending takes place at a rate determined by the nature of the agent and the asphalt as well as by other factors. The reaction will not take place everywhere in the mixture at the same time, but may well occur locally at the interface of the two materials. The differential in consistency inside the mixture is a phenomenon caused by the introduction of the softening agent that is not present in the usual mixture. Since the reaction may take

place slowly in cold mixtures, a new design factor is introduced to accommodate both the initial and long-term properties of the mixture.

A conceptual model was developed, and based upon the model and a literature review, an experiment was designed to observe both the initial and long-term behavior of recycled mixtures prepared by cold processing. As the softening agents, AE-150, AE-300, AC-2.5, and two commercially available agents were used. As a tool of the observation, a creep test was employed and a procedure was developed to analyze the behavior visco-elastically. Blending curves were drawn in which log log of the concentration of the agents was found to be proportional to the viscosity of the blends irrespective of agent types.

The long-term properties of specimens prepared with the different agents were compared. First, the effectiveness of each agent was discussed. The effectiveness was found to be related to the consistency of the old mixtures as well as the nature of the agent. Secondly, an initial softening effect as indicated by strain values higher than the original at a few days of age was explained using a conceptual model. The difference in viscosity between an agent and the old asphalt was found to play an important role in the initial softening

effect. Thirdly, the viscosity of the blend of the agent and the old asphalt was seen to strongly govern the mechanical properties of the recycled mixtures especially at later ages. Also, a trial was made to explain the Hveem Stabilometer values R and S in the hope that they might be used as indices of the long-term observation.

Finally, a design procedure for cold recycled mixtures is proposed which recommends that blending curves be developed to establish a target viscosity and that the design including the use of a non-destructive (creep) test be used to determine mixture properties over at least a few weeks of time.

CHAPTER I

INTRODUCTION

1-1 Basic Concept of Pavement Recycling

Much has been written to describe the background of pavement recycling not only by engineers but also by economists and environmentalists.

The literature may be summarized to conclude that the basic concept of pavement recycling lies in conservation and preservation under certain constraints, i.e., conservation of total energy required to rehabilitate pavements deteriorated through many passes of traffic, conservation of those good materials contained in old pavements, and preservation of its environment by eliminating the necessity for disposing of old materials, while at the same time conserving new materials. Highway engineers, though, are still requested to construct and maintain highways under the concept of conservation and preservation with constraints such that funds are sometimes reduced.

The recycling concept had long been deemed to be ideal but seldom realized due to fact that pavement recycling was more expensive than traditional new construction.

It is now time, however, for such an ideal concept to be realized because of the change of the economic environment, and in actuality, recycling techniques have been developed and widely used in such leading countries as the United States and Japan.

1-2 Function of Softening Agents

Bituminous pavement recycling, when categorized by the procedure used, consists of (a) surface recycling, (b) in-place surface and base recycling, and (c) central-plant recycling (1)*. Each procedure may be accomplished through either a hot or cold process. Irrespective of the processes and procedures, bituminous paving mixtures to be recycled usually contain aged and very much hardened, or highly viscous bituminous materials. Restoration of viscosity is required for the reuse of such mixtures from the standpoint of mechanical properties such as stability, flexibility and durability as well as workability at the time of placement. One of the methods of restoration is to add a material with a lower viscosity to old mixtures.

Materials such as virgin binders in the form of higher penetration grade asphalt cements, cutback asphalts and emulsified asphalts, and various chemical products have been proposed and utilized. Hereinafter the latter will be

* Number in parentheses indicate references listed in the Bibliography.

referred to as "rejuvenating agents" and both of the former and latter inclusively as "softening agents".

The reaction taking place inside a mixture upon application of a softening agent is considered to be solution. The agent reacts with the aged and highly viscous film of a bituminous material which covers an aggregate, and dissolves it, reducing the viscosity locally. Reaction at the interface may occur in a short period, but the deeper portion of the film may react later than the surface, which may cause variation of viscosity inside the mixture. This time dependency of the softening effect might account for unexpected deficiencies in pavement such as lateral flow, or lack of stability in the long run, even when the recycled mixtures shows adequate properties initially. This hypothetical discussion may necessitate observation of recycled mixtures over a long term.

1-3 Conceptual Model of Softening Effect

A conceptual model of the long term effect of softening may be constructed in more detail. The concept may be visualized with Figure 1. An assumption may be made that there are certain limits of viscosity; $\eta_{\max}$ and $\eta_{\min}$. If the viscosity of asphalt becomes greater than $\eta_{\max}$, the mixture may be too hard and cracks will be induced, while, if the viscosity becomes softer than $\eta_{\min}$, instability may result. A mixture with the viscosity of asphalt falling within the limits is expected to be stable. At the time of

FIGURE 1 CONCEPTUAL DIAGRAM
OF SOFTENING EFFECT

the initial construction, the viscosity may well be within the limits. As the oxidation of asphalt progresses, the viscosity increases, exceeding the upper limit at some future time. Deterioration may occur and resotration is required. Recycling is one of the methods of restoration. Upon application of a softening agent, the viscosity initially may fall within the limits, and may continue decreasing gradually over a long term. At the same time, oxidation is taking place within the mixture, causing an increase in the viscosity. Thus it can be expected that the viscosity of the binder after recycling is the result of combination of the two reactions; softening and oxidation hardening. The former will cease at a certain time depending upon the behavior and the amount of the applied agent, which means that the viscosity has a minimum point, designated P in Figure 1. If P stays within the limits, deterioration will not take place, otherwise the mixture will experience a lack of stability and rutting may taken place.

1-4 A Tool to Measure Viscosity

In order to measure the viscosity of the binder, it is possible to perform an extraction test and run a consistency test on the recovered material. The problem with this approach is, however, that it may not reflect the reaction as it occurs. The reaction may be schematically shown in Figure 2. Before being recycled, an aggregate in the mixture is coated with a film of old bituminous

FIGURE 2 SCHEMATIC DIAGRAM OF REACTIONS

material with high viscosity (A). Upon application, the softening agent adheres to the old material and develops a very thin film (B). The softening agent then begins to penetrate into the old material (C). In the long run the outer part of the softened material begins to be oxidized and becomes harder. The steps can be understood by comparing Figure 2 with Figure 1. If the extraction and recovery procedure described above is used, the average viscosity of the blend may be measured and the difference between the steps (B) and (C) may not be distinguished. Here it must be recalled that it is the mixture itself that makes up the pavement, not the bituminous material alone. The above discussion necessitates another procedure which enables the viscosity of the binder to be related to some other properties of the mixture.

One of the possibilities to relate the viscosity of the binder to a mixture property lies in the concept that bituminous mixtures are a viscoelastic material. As will be referred in a later chapter, Wood and Goetz (2) introduced the concept of the Modulus of Recovery and the Mixture Viscosity, in analyzing a static load test (the creep test), by means of the viscoelastic concept and it was shown that a functional relationship between the viscosity of asphalt and that of mixture existed. This suggests the possibility of obtaining the change in the viscosity of asphalt through the viscosity of mixture. The viscosity of a mixture may be

measured employing a creep test, the methodology of which will be described in a later chapter. Since the viscosity of a binder is related in a functional form to the viscosity of mixture, the conceptual model for the viscosity of binder presented in Figure 1 is completely applicable to the mixture.

1-5 Cold Mixed-in-Place Processes

As will be shown in Chapter 2, the proper design procedure for recycled mixture has not yet been established in a satisfactory manner. One of the deficiencies is that any proposed procedures do not take into account the long-term behavior of mixtures. As stated in the previous sections, recycled mixtures behave in a way different from virgin mixtures in principle, and some evaluation procedure of the long-term behavior should be incorporated in the proper design.

It is a well known fact in practice that a virgin mixture made through a cold process takes a longer curing time to obtain a certain level of strength than that made through a hot process. This experience means that a cold recycling process may be more critical in terms of the time to open a recycled road for use after construction.

Thus as discussed, long-term observation is quite necessary in establishing a proper design method, especially in the case of cold processed mixtures. By conducting long-term observations for cold processes mixtures, the behavior

of hot processed recycled mixtures may be revealed eventually.

1-6 Objectives of the Study

The previously listed considerations lead to the proposal of an investigation having the following objectives:

- 1) To observe long-term effects of softening agents on recycled bituminous mixtures produced by a cold process, in which the observed viscosity of mixture may be employed as an index.
- 2) To evaluate effectiveness of both types and amount of various agents.
- 3) To derive some guidelines for the design of cold processed recycled pavement material by carrying out the observations and the evaluations.

CHAPTER 2

LITERATURE REVIEW

2-1 Scope

The first mention of recycling reportedly dates back to as early as 1915 (3). A number of recycling techniques are said to have been patented during 1930's to 1950's (4). However the AAPT, the Association of Asphalt Paving Technologists, had to wait until the year of 1975 for the first report on pavement recycling to be presented at its annual meeting. Recently with the economic climate favoring pavement recycling, much literature both field reports and laboratory investigations have been emerging.

Several investigations have already been made to describe pavement recycling comprehensively (5), but it would still be worthwhile to review literature applicable to objectives of this study. Information, such as properties of old asphalt to be restored, types and properties of softening agents, procedures of mix design used, or even the motivation for employing pavement recycling, needs to be accumulated.

Reviewed in this chapter are field reports, laboratory studies, and techniques for the long-term observation.

2-2 Field Reports on Recycling

2-2-1 Hot Process

Dunning et al (6) presented two experimental projects of pavement recycling by a hot process at the 1975 AAPT Meeting. The subject of this presentation was to describe a recycling operation developed by R.M.I. Systems. A detailed description of mixture design as well as economic considerations was given. The extracted asphalts from the two test sections had the absolute viscosities of 12 kp and 20-155 kp, and penetrations of 22 and 7 to 15, respectively. The rejuvenator Paxole 1009 was used to soften the old asphalt to the desired viscosity (3000-5000 poises). The amount of the rejuvenator was determined using an experimental result that log of the absolute viscosity has a liner relationship with the concentration of the rejuvenator by the weight of the total blend. An asphalt cement, AR 8000, was added to obtain the optimum asphalt content. Though the Hveem Method and the Marshall Method were used in the two projects respectively to determine the optimum content, they proposed a mix design procedure for recycled asphalt pavement using the Marshall Method.

A report by Takeuchi (7) is seemingly the first to describe the recycling of asphalt pavement in Japan. No information is available about the old asphalt properties. The pavement was 5 years old, and repair was required due to heavy damage in the subgrade caused by seepage of water.

Usually this type of repair is done by replacement with new pavement materials, but since excavated pavement materials have been designated an industrial waste by law, dumping these materials was restricted and estimated hauling costs were very high. This situation led to the reuse of the old materials as part of the asphalt treated base course material. About 10 percent of the old material by the weight of total mixture was mixed with the new mixture using a "sandwich" technique, in which the old materials in layers were placed between layers of the new hot mixture in hauling truck. Heat was expected to penetrate into the old materials and a great success was reported.

Large cities in Japan are still developing. Excavation of roads is seen everywhere so as to construct subways, sewerage systems, or intra-city expressways. The common trouble in those cities is the difficulty in disposing of the excavated pavement materials. Kuroda et al (8) report the reuse of excavated pavement materials in Osaka, Japan. The excavated materials consisting of surface, binder and asphalt treated base-course materials from various roads were collected. Asphalts were extracted, and the average penetration was found to be 30, though much variation existed. By trial and error it was decided to add 0.8 percent of asphalt cement having a penetration of 60-80, 0.2 percent of waste oil from an oil heater and 8 percent of sand to make a light traffic road material by a hot process.

The Marshall stability test was performed on the mixture and the stability and flow values were found to be greater than those of the modified Topeka, a commonly used mixture in city streets in Japan. Based on these results the danger of evaluating the strength and durability of recycled mixtures solely on the basis of the Marshall Stability Test was pointed out. Kiriya and Oya (9) report a recycling project in Nagoya, Japan. The pavement material restored was a material placed tentatively to cover a subway construction section, and was one year old. The original asphalt with a penetration of 60-80 had dropped to 58. The Marshall Method (modified in Japan) (10) was employed in designing the mixture. To make coarse graded asphaltic concrete, 1.3 to 1.4 percent of virgin asphalt cement and about 30 percent of virgin aggregate was added in a hot process.

Kiya et al (11) describe experimental projects of recycling in Chiba Prefecture, Japan. Chiba is a developing prefecture and the wasted asphalt pavement mixture amounted to 80,000 metric tons during 1976. The excavated mixture, designated as an industrial waste, had to be hauled a long distance to a specified place. This resulted in high transportation cost and also created a secondary environmental problem due to hauling traffic. The prefecture has decided to develop a comprehensive recycling system of waste pavement materials, and the projects described are the beginning experiment. Seven roads were selected and 100 X 100 samples were taken and several tests were conducted. Extracted

asphalts showed the penetration ranged from 22 to 137, mainly from 30 to 50. A softening agent, the properties of which are unknown, was added to increase the penetration to certain levels (70 or 90), making use of the experimental result that log of penetration shows linearity when plotted against the percentage of the agent by weight of the original asphalt cement. The Marshall Design Method (modified in Japan) was employed to determine the optimum asphalt content, and the amount of additional asphalt cement (Pen 60-80 or Pen 80-100) was decided by subtracting the original asphalt content and the amount of the rejuvenator from the optimum asphalt content. The mixture made with a hot process was placed in three locations and was found to be very effective. Chiba Prefecture has already adopted the tentative specification for the recycled asphalt pavement materials.

Whitcomb et al (12,13) reported the first hot-mix asphalt recycling project in Oregon. It was decided to recycle 45,000 metric tons of asphalt concrete pavement placed for temporary purposes in the rehabilitation of I-5. The extracted asphalt showed an absolute viscosity of 7000 and 7700 poises, and a penetration of 46 and 50. The Oregon mix design procedure (a modified Hveem Method) was used to determine the optimum asphalt content and the difference between the optimum content and the asphalt content of the original mixture was satisfied with addition of AR-2000. Also 0 to 20 percent of aggregate was added.

One of the conclusions was, "The properties of slightly aged asphalt cement can be adequately modified through the addition of new 'soft' asphalt cements without incorporating recycling additives." It must be noted that higher asphalt contents were necessary to maintain good workability because mixing had to be done at lower temperatures inside the drum to reduce opacity and particulate emissions.

Kudo (14) reports their experience at a recycling asphalt plant in Tokyo, Japan. His report described a new recycling plant system in which pulverization is accomplished using steam, and heating is done indirectly in a dryer. The asphalt pavement materials brought to their plant to be recycled had an average penetration of 30 with the standard deviation of 7. Most of them were around 10 years old. He also reported that one of two types of oil is usually added to recover the penetration. The two types of oil were selected after their own investigation which included more than ten oils both mineral and vegetable.

2-2-2 Cold Process

Davidson et al (15) reported a field trial in California in which their design procedure was necessary due to the pavement failure. A two-inch asphalt concrete overlay and 4-inch road mix surface was excavated and was reclaimed in a cold process with an emulsified reclaiming agent. The reclaimed mixture was used as a base course. The extracted asphalt had an absolute viscosity of 1105 poises and a

penetration of 118. The amount of the agent to be added was determined by subtracting the asphalt content of the old pavement from the asphalt demand of aggregate, which could be calculated by either the CKE procedure or a mathematical formula based upon the gradation of the aggregate. It was noted that on-grade, cold recycling would be accepted particularly for reconstituting secondary roads, road mixes and shoulders. The author reported however that "the cold recycling process presents more uncertainties in obtaining adequate and uniform incorporation of reclaiming agent into asphalt than does hot mixing."

Hara et al (16) report on an on-grade, cold recycling project on a secondary road at Hakone, a national park area, in Japan. The old asphalt pavement exhibited alligator cracking over the surface and rehabilitation was required. Complete replacement would have been utilized but, since dumping excavated pavement materials is prohibited within a national park, the hauling cost was estimated to be very expensive and it was decided to utilize the existing material as a base course by an on-grade, cold recycling process. After trial mixing it was decided to add 10 percent of aggregate (Crusher run 30mm - 0mm), 3 percent of Portland cement and 5 percent of a cationic emulsified asphalt. After compaction, the reclaimed base was seal-coated, cured for 6 days under traffic, and then covered with a 3cm thick surface course.

In a comprehensive study, Yamane and Yoshikane (17) demonstrated an example of a recycled surface course by a cold process. Three percent of an emulsified asphalt and 5 percent of water was added to 100 percent of crushed pavement. The mix design procedure was not explained but the asphalt content was supposedly calculated with a mathematical formula based on aggregate gradation. The Marshall stability was examined and the mixture was found to satisfy the specified standards.

2-2-3 Summary

Based upon the literature reviewed, the following items may be highlighted:

- 1) The field reports cited discuss several experimental projects. The choice to use a particular recycling process depends upon various factors. Sometimes, very young mixtures can be easily recycled, while at other times old mixtures must be restored. The cause of deterioration is sometimes found in the asphalt mixtures and sometimes in the lower layers.
- 2) The consistency of the asphalt contained in pavement materials to be recycled as measured by either the absolute viscosity or the penetration varies over a wide range due to various factors.
- 3) Softer asphalt materials are always added to old mixtures and rejuvenating agents are often employed.

- 4) Especially in hot processes, conventional design procedures such as the Hveem and the Marshall Methods are extended to the design of recycling mixtures.
- 5) Recycling procedures, including the selection of softening materials, may be different depending upon the binder consistency.

2-3 Laboratory Studies

2-3-1 Sequence of a Design Procedure for Recycling

The whole sequence of tests required to design recycling mixtures is not difficult to demonstrate. Epps et al (18) presented a flow diagram of a testing program in 1976, and this was later followed by Davidson et al (15), Kennedy and Perez (19), and Epps et al (5). The sequence of tests proposed are very similar in many phases and may be summarized as follows:

- 1) Obtain representative field samples of mixtures to be recycled and extract asphalt and aggregate to analyze gradation, asphalt content and consistency.
- 2) Determine the properties of the new mixture and the type of softening agents. Analyze virgin aggregate and the softening agents. If necessary, establish blending curves.
- 3) Design the mixture and determine the proportions of the mixture. Conduct mechanical tests if required.
- 4) Evaluate the results and make decision.

Literature concerning laboratory studies will be cited in the expansion of the sequence of the procedure.

2-3-2 Sample Acquisition

All of the researchers acquired pavement mixtures for laboratory studies from nearby highways without any exceptions. Some (4,20-23) obtained only one pavement sample, while the others (15,19,24-25) obtained two or more samples from various highways. Terrel and Fritchen (20) claimed that their sample taken from a county road was representative of one of the most extreme cases to be encountered in practice with alligator cracking of medium severity and some ravelling after 15 years service. The extracted asphalt had a penetration of 17 and an absolute viscosity of 21528 poises. However, it was found that 16 samples from different locations acquired by Davidson et al (15) had penetration values ranging from 7 to 215 with a coefficient of variation of 106 percent and absolute viscosities from 301 to 254000 poises with the coefficient of variation of 244 percent. Since recycling procedures may well be different depending upon the consistency of asphalt in mixtures to be recycled, the above discussion points out that there is no general rule in claiming that a certain pavement section will be representative of what would be encountered in practice. This is compatible with the earlier observation that the decision to use a certain recycling process depends upon various factors.

It must be further noted as Anderson et al (25) point out that some pavement materials may show great variability in their properties, which may well confound the test results after recycling, especially if the effect of recycling is the only factor being sought.

2-3-3 Specimen Fabrication

When specimens with a standard dimension of 4 in. (10.2cm) in diameter and about 2.5 in. (6.4cm) in height are required, most researchers utilize conventional methods, or modifications (4,20) of the Marshall compactor (4,15,25), the California kneading compactor (20), or the Gyratory compactor (19,21). Davidson et al (4) used a modified Marshall procedure at different mixing and compaction temperatures (250 F and 220 F) in order to incorporate emulsified reclaiming agents. Terrel and Fritchen (20) compacted their specimens to be subjected to accelerated aging by a modified method. Crushed pavement and additional aggregate were heated in a 275 F (135 C) oven for one hour. During the last 15 min. of period, a predetermined amount of a rejuvenating agent was heated to about 220 F (94 C). At the end of the one hour, the agent was added to the pavement material and then the mixture was placed back in the 275 F (135 C) oven for 30 min. The mixture was compacted with the California kneading Compactor with the peak foot pressure of 350 psi (24.6 kg/cm) instead of ordinary pressure of 500 psi (35.2 kg/cm).

The specimens were cured at 73 F (23 C) for about two weeks.

Tia (21) and Tia et al (22) are the only ones who have developed a sample fabrication technique for use with a cold process for laboratory-use specimens. The basis of the procedure relied on the cold asphalt mixture design using emulsified asphalts developed by Gadallah (26). The detailed procedure will be discussed in Chapter 5. Tia examined various compaction methods. The three compaction methods, The Marshall, the Hveem Kneading and the Gyratory compactors, were compared and the Hveem method was ruled out because the asphalt binder and pavement material tended to stick to the foot of the compactor due to no heat being applied to the system in a cold process. It was stated that the Marshall test was unable to detect mixtures that would be unstable in the future (22). The Gyratory compactor was chosen as it was found to produce consistent samples.

2-3-4 Mix Design Procedures

The term "mix design procedure" here is used in a narrow meaning; it refers to action of proportioning pavement materials, softening agents, and virgin aggregate if any. In this meaning, only a few laboratory investigations have been made. Field reports appear to be more valuable for references.

Dunning et al (16) developed a mix design procedure using the Marshall Method as was cited earlier in 2-2-1.

This procedure is basically the same as employed by Kiya et al (11).

Davidson et al (4) established another procedure. The design consisted of determining the asphalt demand of the aggregate contained in the old pavement by means of the CKE method or a mathematical formula (15) and determining the amount of a reclaiming agent using nomographs. To do this, tolerable consistency limits for the reclaimed asphalt must be predetermined. The nomographs are nothing but blending charts and they were established through their experiments. The difference between the original asphalt content and the asphalt demand is to be offset by an agent and its viscosity may be determined with the nomographs.

The same procedure as cited above is presented in another reference (5). However, the use of a standard stability test including the void ratio determination was proposed, though the detailed description was not available.

The following references are not mix design procedures, but are cited as various methods of fabricating specimens for different mechanical tests. The procedure followed by Tia (21-22) is an extension of a conventional mix design. Several levels of softening materials, e.g., 0.5%, 1.0%, 1.5%, by the weight of mixture were added to old pavement mixtures. This is basically equal to the procedure used

in Oregon (12). Carpenter and Wolosick (23) determined the amount of the rejuvenating agent, Paxole 1009, to be added to the salvaged material by means of a blending curve they established. The amount was determined so as to produce an absolute viscosity of 1000 poise at 140 F (60 C) corresponding to an AR-1000. However no reasoning was presented to justify this level and it was not stated whether it was optimum in the mixture or not. This was also the case for the study by Anderson et al (25).

A summary of this paragraph would include the following:

- 1) The concept developed by Dunning et al (6) is applicable in cases where two or more softening agents are to be used. The other procedures are basically applicable when a single softening agent is to be used.
- 2) Though the CKE method is often used in designing virgin mixes, the resulting asphalt demand is usually checked by means of the stabilometer and the CKE method does not always give the optimum asphalt content. Furthermore, in order to determine the asphalt demand, the viscosity of the asphalt must be known previously, which in turn is difficult with recycled mixtures because the viscosity of the new blend can not be determined until the amount of the softening agent is determined. Thus it should be concluded that the stability and void ratio must be checked at all times especially in recycling.

- 3) The method employed by Tia is appropriate to determine the long-term response. However, with this method it is difficult to designate the viscosity level of the blend in the recycled mixture.
- 4) The use of blending charts is an easy way to obtain a certain level of viscosity but there was no reasoning why a certain level of viscosity should be selected as an optimum.
- 5) Softening agents are used to secure appropriate mix properties and workability. These requirements may be met by using two or more softening agents which results in wider applicability. This requires the use of the design procedure developed by Davidson et al (4).

However, it must be noted that the system becomes the more complicated when more constituents are added. A rejuvenating agent added to an old mixture in order to reduce the viscosity of the old asphalt does not work only against the old asphalt but may react with a virgin asphalt cement newly added resulting in the reduction of its viscosity. In this respect, a conclusion made by Davidson et al (15) that a "one-component reclaiming agent can be used as the sole additive, a method of recycling which has advantages over the use of two additives" is worth noting.

2-3-5 Mechanical Properties

Mechanical properties evaluated so far are the Marshall stability (4,24-25), the Hveem stability (21-22,24), the resilient modulus (20,24-25), the creep compliance (25), the direct tension tests (19), the splitting tension or indirect tension tests (24), and water susceptibility (22,24).

The merit in using conventional design indices such as the Marshall or the Hveem stabilities may exist in the similarity of design procedures. The Marshall stabilities of recycled specimens fabricated by the procedure proposed by each researcher are reported to fall within reasonable limits. Furthermore, recycled mixes are reported to have higher flow values (4,8,9,14,17,24) and higher stabilities (8-9,14,17) compared with the virgin samples. Davidson et al (4) argued that the high flow values may be inherent in recycled mixes. Kuroda et al (8) claimed that evaluating the strength and durability for recycled mixtures by means of the Marshall stability test is dangerous because hard mixtures lacking in viscosity tend to show high stability and low flow values.

Using cold processed mixtures, Tia et al (22) reported that the amount of softening agents are most important in the evaluation of the Hveem stability. This suggests that by this method an optimum binder content can be obtained. But it must be noted that the curing time was also found

significant when emulsified asphalts were used. It was also found that the possibility of testing the same specimens more than once in the stabilometer should be ruled out. They also disclosed (22) that the content of a softening agent yielding the highest Hveem R-value increases as the level of weathering of the old pavement increases. They claim that this fact means that a more oxidized pavement has a lower effective asphalt content and thus requires more agent to reach the optimum effective content.

The resilient modulus has been widely used in evaluating bituminous mixtures. Since the modulus has been related to pavement design procedures using the multilayer elastic or finite element methods (20), it may be useful in pavement design for recycled mixtures. No consistent conclusions among the various researchers have been obtained, however, when the resilient modulus tests were performed on recycled mixtures. Kennedy et al (19) report higher modulus values for recycled mixtures than for virgin mixtures. The binder viscosity is reported to affect the resilient modulus (24-25). An advantage of the resilient modulus lies in its non-destructive nature, enabling the same sample to be tested repeatedly. Terrel and Fritchen (20) made use of this point which will be discussed in the next section.

The creep compliance is a function of the compressive strain divided by a constant load. Anderson et al (25)

found that the asphalt consistency seems to have a significant effect in that the softer the binder becomes the more readily the material deforms under loading.

Kennedy and Perez (19), using static and repeated indirect tension tests, report that the tensile strength, static modulus of elasticity, resilient modulus and fatigue life are all effected by amount and type of softening agents, and that all those properties decrease linearly with the increase in the amount of the agent.

Water susceptibility was evaluated by means of the vacuum saturation method by Epps et al (24) and Tia et al (22). Epps et al (20) found that the Hveem stabilities remained practically the same or decreased only slightly after the soaking. They point out the possibility of something existing in the recycling process that improves water susceptibility. Tia et al (22) found that the resistance to water in terms of the retained Hveem stability values increases with increased binder content.

2-3-6 Effects of Aging After Recycling

As was described in Chapter 1, the reaction of softening agents is physico-chemical in nature and is time dependent. Several investigations have been made with the above concepts in mind.

Davidson et al (4) called this physico-chemical phenomenon the fluxing phenomenon, and stressed the importance of some understanding of the mechanics of the process. A laboratory test was established, in which the

fact that certain components of reclaiming agents fluoresce under ultraviolet light was employed as the experimental technique. Briquette shaped specimens were prepared using artificially aged asphalt and ottawa sand, cured and an emulsion of a reclaiming agent, the composition of which was unidentifiable, was added. Specimens were placed in an infrared oven at 140 F (60 C) for selected time intervals and broken to be photographed under ultraviolet light. It was found that fluxing takes place gradually by migration even without mechanical mixing. The time necessary to reach equilibrium depended upon the concentration of rejuvenating agent, and that there was a maximum amount of recycling agent that could be assimilated by an asphalt.

Terrel and Fritchen (20) put recycled specimens with Paxole 1009 and Reclamite and virgin specimens in an oven kept at 140 F (60 C) and at the end of selected time intervals subjected them to the resilient modulus test. This was done to better understand the fluxing phenomenon. It was found that the specimens fabricated with standard AR-2000 and AR-4000 paving grade asphalt showed a gradual decline in the modulus while the specimens fabricated with selected amounts of rejuvenating agents showed a gradual decline in the modulus for the first 48 hours and then exhibited an increase. The behavior was observed for 64 hours. It was claimed that the asphalt cement and rejuvenating agent continued to react inside the specimen and that

as the time increased, the rehabilitating effect of the rejuvenating agent begins to decline and the asphalt cement once again begins to oxidize and the asphalt becomes harder. It was noted that aging of the recycled asphalt pavement specimens appears to have been delayed by the presence of rejuvenating agent in the mixtures, i.e., a lower asphalt viscosity for a longer period of time is maintained.

Anderson et al (25) observed the effect of recycled materials due to aging. The samples were fabricated using highway materials with five different additives and without additives, and subjected to aging for the first six weeks in outside conditions and then in an oven at 140 F (60 C) up to 6 months. The Marshall Stability, the creep compliance and the resilient modulus were observed. The Marshall Stability was observed to have increased for all mixes, and no drastic difference in the increase in stability could be determined among the various agents. The mixes decreased in creep compliance with aging over the six month period, demonstrating a hardening effect. The no-additive and AC-5 mixes showed an increase in the compliance at one second during the first three months, and decreased during the second three months. It was found that the mix containing Reclamite decreased the most. Except for mixes with no-additive and AC-5, the resilient modulus showed an increase during the whole period which means a stiffening of the mix

due to the heat aging. Reclamite again showed the highest increase.

The study by Carpenter and Wolosick (23) was presented at the 59th Annual Meeting of the Transportation Research Board in January 1980 and was not available when this study was begun. However, it will be worthwhile to cite some results from their work, because their conceptual model was found to start from an almost similar point as this study. They call the softening phenomenon the diffusion phenomenon, which is considered to be of a time-dependent nature resulting in alteration of viscosity in a film of asphalt. To examine the diffusion process, a pavement material was acquired from a nearby city street, and the rejuvenating agent, Paxole 1009, was added in a hot mix so that the blend viscosity becomes 1000 poises which corresponds to AR-1000. After compaction by the double ended static method, the resilient modulus, the creep compliance, and the Marshall Stability were observed for about 50 days. The resilient modulus values for the recycled samples showed a dramatic variation with time; the day following preparation the modulus is high, and with time it decreases, and finally increases again. The creep compliance, however, showed essentially no variation with time. The Marshall Stability and flow values did not show any meaningful variation either. The fact that the resilient modulus exhibits the variation with time while the creep compliance does not is

attributed to the former being a tensile test while the latter is a compression test.

2-3-7 Summary

The following items may be summarized in this section;

- 1) The researchers are almost all of the similar opinion with respect to the sequence of the design procedure in general terms, but agreement has not yet been reached in detailed procedures. No standard design procedures have been established as yet.
- 2) Samples are obtained from existing highways, though variabilities in their properties are known to exist.
- 3) A standard sample of 4 in. (10.2cm) in diameter and 2.5 in. (6.4 cm) in height is usually employed, and standard fabrication methods are used with some modification. Each researcher uses his own modification.
- 4) Proportioning is accomplished, in general, by two conventional methods with some modification and by using a blending chart. These have been discussed in the section 2-3-4.
- 5) Many indices are proposed to evaluate the mechanical properties of recycled mixtures, but no methods can be called as representative.
- 6) Though long-term observations have been made with recycled mixtures, most researchers are concerned with explaining the fluxing phenomenon, and few efforts have

been made to correlate the results with mix design parameters such as stability, strength or flow values.

2-4 Rejuvenating Agents - The Basic Concepts

2-4-1 Asphalt Chemistry - Colloidal System

Rejuvenating agents are chemical products, consisting mostly of aromatic hydrocarbons. The reasons for employing such agents were described by Davidson et al (4), 1) to bring the asphalt to its optimal chemical composition for durability and 2) to restore the asphalt characteristics to a consistency level appropriate for the mix. A knowledge of asphalt chemistry especially describing the hardening process of asphalts is necessary in order to understand the function of rejuvenating agents inside the recycled mixtures. Pfeiffer (27) indicates that most asphalt bitumens are colloidal systems, in which the disperse phase, called the micelles, is formed by a complex of the asphaltenes and high molecular aromatic components of the maltenes, and the continuous phase, or the intermicellar phase, consists of the lower molecular constituents of the maltenes. He continues that, if the micelles are well peptized, the bitumen behaves like a sol, while if they are partly flocculated, a more or less rigid structure is apt to be formed and the bitumen behaves like a gel. Complete peptization of the micelles is possible, according to Pfeiffer and Saal (28)*, if the system contains enough aromatic

* A reference in (27)

constituents to saturate adsorption forces of the asphaltenes, otherwise, mutual attraction between the micelles occurs leading to formation of a gel structure, or precipitation of asphaltenes.

The asphalt which behaves like a sol can be considered to form lyophobic colloids, where the term "lyophobic" means solvent-hating (29). In a lyophobic system, the dispersed particles tend to stay separated from each other and the rate of flocculation may be very slow. A physico-chemical explanation of this system is the equilibrium of attraction due to van der Waals forces and repulsion due to the electric field around each particle (29). Though the rate of flocculation may be slow, flocculation may occur in the long run, thus causing precipitation of asphaltenes and formation of gels.

2-4-2 Causes of Hardening

Traxler and Schweyer (30) describe a phenomenon called "time-hardening". This phenomenon occurred when asphalts were maintained undisturbed at 25 C (77 F), and the viscosities were found to increase with time. The rate of increase is found to be very rapid immediately after the material has cooled, but to slow down as time increases. They argue that the progressive increase in the viscosity is probably caused by the formation of a structure within the bitumen.

They also found that gentle reheating of the samples brought the penetrations back almost to the original values. Brown et al (31) refer to this "time-hardening" phenomenon as "steric hardening" and describe it as a reversible hardening resulting from internal physical reorientation and reorganization without dimensional deformation at the atomic, molecular, and micelle levels. Since a micelle has a crystalline structure (32) like a discrete gel particle, the steric hardening may be described as the reorientation and development of micelles resulting in thermodynamically reversible gels (32). It must be noted that Traxler and Schweyer (30) also found that upon reheating, asphalts, which had time-hardened for several thousand hours, lost a large percentage of the viscosity which had developed during aging. They attributed this permanent hardening to evaporation or other changes in the asphalt.

Another phenomenon, called syneresis, is also believed to take place inside some asphalts when they are kept undisturbed. Syneresis is defined as the spontaneous separation of an initially homogeneous colloid system into two phases, the micelles and the intermicellar phases (33). This phenomenon is reversible if the colloid particles do not become too coagulated after their formation, and there is no net volume change (33). Along with the classification of the types of syneresis given by Heller (33), syneresis in asphalt may be caused by aggregation

of micelles, or discrete gel particles, uniting into a denser gel portion which is a contraction of the micelle part, and squeezes out the intermicellar liquid. The discussion may suggest that the steric hardening is a cause of syneresis, but syneresis may not always take place even when steric hardening occurs. The squeezing of the intermicellar phase may depend on various factors such as the ratio of constituents. It must be kept in mind that generally, syneresis is followed by rather slow coagulation (33). This indicates that the syneresis may cause irreversible hardening during a long pause after the initial formation of gel portion.

Polymerization is another cause of hardening. Polymerization is thought to occur by one of two types of mechanism (29). One of the mechanisms is a free radical process. Radicals may be generated by chain scission with the assistance of oxidation or heating, or irradiation (32). Radicals formed in molecules tend to connect each other resulting in the formation of cross-linked chains. This cross linking yields polymerized molecules with high molecular weights. A second type of mechanism is where a strong acid adds a proton to monomers and polymerization takes place in a similar manner (29). An empirical equation developed by Sakurada and Houwink (32) states that the intrinsic viscosity of polymers $[\eta]$ is related to the molecular weight M in such a manner that $[\eta] = KM^a$, where K and a are constants in a

given solvent. This indicates the more oxidized, or the more polymerized a polymer becomes, the more viscous it will be. Though the composition of asphalt cannot be discussed in such a term as monomers, it may well be imagined that similar reactions are taking place inside asphalt when it is exposed to heat, air (oxygen), light or other physical actions, and that the asphaltenes are now large molecules with high molecular weight, causing high viscous behavior.

So far only asphaltic bitumen has been taken into account. When it is heated and mixed with mineral aggregate, other complicated physico-chemical phenomena may take place. One of them is selective absorption of an oil portion by the aggregate (34). The capillary force at the surface of aggregate absorbs the intermicellar portion in the asphalt colloid, which may stimulate the exuding of the intermicellar liquids. This may cause an unbalance in the colloid system, resulting in more hardening by the remaining part. Furthermore mineral aggregate surfaces are reported to act as a catalysis for the oxidation of asphalts (35). Heating an asphalt causes volatilization of an oily fraction, and may also assist oxidation. These are some of the causes of asphalt hardening.

2-4-3 Changes of Composition of Asphalt with Aging

Though Pfeiffer classified the constitution of asphaltic bitumen into only two parts, asphaltenes and maltenes, further classification of maltenes is possible. There are

several procedures for the fractional chemical analysis of asphalts and comparative results indicate that different procedures often result in fractions and in the naming of each fraction. The procedure developed by Rostler (36-37) is one of the most widely cited in literature. According to the Rosler's procedure, an asphalt may be separated into five fractions, each identified with an initial letter, A, N, Al, A2 and P. Fraction A is asphaltenes, a bodying agent, and the other fractions as a whole are referred to as maltenes. Fraction N stands for nitrogen bases and is the most reactive fraction. This is believed to be the peptizer for asphaltenes (37). Fractions Al and A2 are the first and the second acidaffins and are the solvents for peptized asphaltenes. A2 is slightly unsaturated. Fraction P stands for paraffins and is the gelling agent consisting of saturated hydrocarbons. It was found that in the aging process, fractions A and P are the most stable components, and that fraction N is the most reactive, and converts most rapidly into A. Fraction Al converts into N (37). The observation that the nitrogen bases are transformed into asphaltenes with aging is of great importance. Since the nitrogen bases are the most reactive fraction, they may be cross-linked with asphaltene molecules or with other nitrogen bases, resulting in coagulation. As the nitrogen bases are the peptizing agent, the dispersing ability will be being lost as the aging progresses.

2-4-4 Function of Rejuvenating Agents

The previous discussion constitutes a basis used by many researchers for explaining the function of rejuvenating agents. Dunning and Mendenhall (38) state that the approach best suited to recycling asphalt is to improve the ability of the maltene phase of an aged asphalt to disperse the asphaltenes. Based on this statement they conducted an experiment and concluded that modifiers with a polar compound (corresponding to the nitrogen bases) content of 9 percent minimum, an aromatic compound (corresponding to the acidafins) content of 60 percent minimum will accomplish the above requirement. Terrel and Fritchen (20) reported that during the process of weathering or oxidation the ratio of maltenes to asphaltenes is reduced which results in a dry and brittle pavement and that a successful rejuvenating agent must contain sufficient maltenes fractions to improve and restore the ratio. Gannon et al (3) state that peptization of asphaltenes is achieved easier when recycling agents with large percentages of aromatics and relatively small percentages of polar compounds are used instead of AC-5 containing a greater percentage of polar compounds. This observation is equivalent to a statement by Dunning and Mendenhall (38) that oxidized asphalts require a solvent of greater aromaticity than do asphaltenes of neat asphalt. It is interesting to note, however, that Davidson et al (4) state that the use of so-called "highly aromatic

oils" is open to question because this can result in mixes which are highly susceptible to aging. They (4) also noted that reclaiming agents containing controlled amounts of asphaltenes were found to be promising because adding asphaltenes prevents recycled mixtures from having too low a consistency which could occur if only maltene portions were added to aged asphalt. This may indicate the possibility of using a single softening agent instead of using both a virgin asphalt cement and a rejuvenating agent.

2-5 Blending Curves and Charts

2-5-1 Classification of Blending Curves

It was found through the literature review that many studies have been proposed for using various types of blending curves or charts to design recycled mixes, especially with rejuvenation agents. Most of them show some relationships between the concentration of softening agents and the consistency, in terms of viscosities or penetration values, of the blend which contains the agent and the asphalt cement in the old pavement material.

The blending charts for viscosity may be classified into four general types:

(a) Linear functional form (1)	ASTM D 341-43 type
(b) Linear functional form (2)	log of viscosity type
(c) Linear functional form (3)	log (log of viscosity)
type
(d) Non-functional type	

Literature is reviewed in the order of the above listing. The charts for penetration values follows.

2-5-2 ASTM D341-43 Type

Blending of oils has long been done in the field of mechanical engineering to prepare appropriate lubrication oils. A number of formulae and charts have been developed to predict the required composition of a new two-component lubricating oil blend or to estimate the composition of an existing oil blend when the viscosities of the two components are known (39). One such chart is the Standard Viscosity Temperature Chart for Liquid Petroleum Products, specified as ASTM D341-43, which was replaced with ASTM D341-74. The old ASTM charts were drawn based on the experimental relationship given (40) by

$$\log \log(\text{kinematic viscosity in cSt} + \text{const.}) = A - B \log T$$

where A and B are determined by measuring viscosities at different temperatures, T is the temperature in Kelvin degrees, and the constant varies from 0.6 to 0.7 depending on the viscosity range of each chart. In the Appendix of ASTM D341-43, it was written, (but now deleted in the new edition), that those viscosity-temperature charts may be used for estimating the viscosity of blends of petroleum at a given temperature when the viscosities of the components at the same temperature are known. For this purpose,

the 0 F line may be assumed to represent 100 percent of the lighter component and the 100 F line to represent 100 percent of the heavy component. The known viscosities of the two components are plotted on the proper lines at points corresponding to the value on the viscosity scale, and a straight line is drawn through them. Points on this line show viscosities of blends of the particular components at the given temperature, depending upon the proportion of the light and heavy component.

Dunning and Mendenhall (38) utilized the charts in their evaluation of asphalt-modifier blends. They state that a plot of $\log \log \eta$ versus $\log(559.7-p)$ gives a straight line or very close to a straight line, where η is the viscosity of the blend in centisokes and p is the percent of the lighter oil. In an equation form:

$$\log \log \eta = A + B \log(559.7-p)$$

They prefer $-\log(559+2p)$ to the former, $\log(559.7-p)$, however. They define the effectiveness of a modifier by dividing the measured viscosity of a blend by the viscosity predicted by the above equation, and conclude that paraffinic oils (i.e., oils with a high content of the fraction P) result in a detrimental effect on asphalt if added as recycling modifiers.

Attention should be directed to the procedure of taking the section between 0 F and 100 F in ASTM D341-43

charts. This was quite an arbitrary selection, and no theoretical or physico-chemical reasonings for this conventional method have been given. The reader was cautioned in an article (41) that any chart is at best only a close approximation. This should not be forgotten when reading the following sections.

2-5-3 log n Type

Dunning et al (6) proposed a mix design procedure for recycled asphalt pavements based on their study using the extracted asphalt from a test section and Paxole 1009 as the softening agent. The procedure for determining a softening agent concentration requires a plot of the absolute viscosity of the blend versus the concentration of a softening agent on semilog graph paper. The range of concentration of a softening agent recommended by the design procedure is 0 to 20%. This means that the linearity between the log of viscosity and the concentration may hold for this range.

Terrel and Fritchen (20) employed the experimental result by Dunning et al (6) and showed a viscosity blending chart, with which they determined the amount of rejuvenating agents (Paxole 1009 and Reclamite). The figure presented in the literature (20) has the abscissa of percent rejuvenating agent in the blend from 0 through 100 instead of the percentage from 0 through 20 used by Dunning et al (6). Terrel and Fritchen seem to have extended the

experimental result by Dunning et al presumably without additional experiments.

2-5-4 log of log η Type

Davidson et al (4) present their experimental results in a form of a viscosity blending chart. The results indicate that virgin and artificially aged asphalts, and asphalt extracted from an aged pavement, show a linear relationship between log log of the absolute viscosity and the weight percent of reclaiming agent in the blend. They established a viscosity nomograph to predict 140 F viscosity of a recycled asphalt or of a reclaiming agent. The nomograph made use of the fact that the blending curve can be determined by simply connecting the viscosities of asphalt and of a reclaiming agent with a straight line. This fact means in other words that a blending curve can be determined once two viscosities at two different concentrations of a rejuvenating agent are measured. Another type of the viscosity blending chart has been proposed. The chart is presented in an article (5), and was cited from the West Coast User Producer Group. The ordinate of the chart is in log log of kinematic viscosity at 140 F while the abscissa is in linear scale of volumetric percentage of the lower viscosity component. It is not clear whether the charts by Davidson et al and by the West Coast User Producer Group were developed independently or not.

2-5-5 Non-functional Type

Anderson et al (25) added various amounts of softening agents, including flux oil, dust oil, and two other commercially available agents to asphalt extracted from mixtures. The absolute viscosity at 140 F was plotted as the ordinate versus the percentage of the agent by weight of the total mixture, both on a linear scale. They obtained continuously decreasing curves with different shapes. From these curves the percentage of each softening agent was determined in order to obtain predetermined target binder consistencies. It must be pointed out that in determining the percentages of the agents no functional form was assumed for the curves; thus the curves were used experimentally only.

2-5-6 Blending Charts for Penetration

It is a common practice in manufacturing petroleum asphalt to blend two or more stocks and blending charts may be used to estimate blending proportions to achieve a desired penetration after mixing. One of them, which is presented in an article (42), utilizes special curves which connect the penetration of the two asphalts plotted in the linear scale as the ordinate, while the abscissa is the volume percentage of each component in a linear scale. A different chart is used in Japan (43). Both charts utilize special curves which may have been obtained through

experiments, and no functional forms are assumed. Dunning et al (6) present a figure in their study in which log log of the penetration has an almost linear relationship with the concentration of the agent. The experimental work seems to have been conducted with the concentration of up to 30%.

Davidson et al (4) developed a penetration nomograph based on the results of their study. In order to secure the linearity, they employed a special scaling in the ordinate for penetration at 77 F, while the abscissa is linear and is for the percentage of the total asphalt in the mix. This nomograph lacks generality, however, because different charts should be prepared for agents with different viscosities. This trouble may be caused by the fact that penetration cannot be measured for such soft materials.

2-5-7 Summary

Several blending charts have been presented in this section. Except those for lubrication oil and for asphalt blending, all the charts or curves have been developed as a result of investigations of recycling. With respect to these charts, the following should be borne in mind:

- 1) The charts are applicable to rejuvenating agents including oils. However, none are available for the use of asphalt cements or emulsified asphalts as softening agents.

- 2) Most researchers prefer viscosity, either absolute or kinematic, to penetration. This may be because of the difficulty of obtaining the penetration values of rejuvenating agents.
- 3) Certain functional forms relating consistencies of a blend to concentration of added softening agents are predicted, but no physico-chemical interpretations have been made as to why the blends follow such forms.
- 4) It can not be determined which chart should be employed in practice.
- 5) All the investigators implicitly assume that the blends are homogeneous. This assumption is suitable when establishing the blending curves, but it may not be true in practice when it comes to mixing rejuvenators with the old mixtures.

2-6 Test Procedures for the Determination of Various Mechanical Properties

2-6-1 Scope

Non-destructive test procedures were sought to evaluate long-term behavior of the specimens. As such, the resilient modulus and the creep behavior, are the two possible ones among those proposed in the literature quoted. The two will be briefly reviewed here.

2-6-2 The Resilient Modulus Test

Ever since Schmidt (44) proposed a practical method, the resilient modulus has widely been utilized in the study

of bituminous mixtures as a tool to evaluate them as well as to relate their properties to pavement design methods. The resilient modulus is simply the modulus of elasticity when the theory of elasticity is applied to bituminous mixtures to analyze the stress-strain relationship. The modulus of elasticity E of a thin disk was derived (44) using analytical work by Timoshenko and Goodier (45). The work described a disk with two equal and opposite point forces acting across a vertical diameter. The modulus of elasticity E of a thin, homogeneous disk is given by the equation;

$$E = P \left(\nu + \frac{4}{\pi} - 1 \right) / t \Delta$$

where ν is the Poisson's ratio, t the thickness of the disk, and Δ the horizontal deformation. In the practical procedure, the load is applied in a line form and either statically or dynamically instead of point and static loading. Though Schmidt (44) suggests the use of 0.35 as the Poisson's ratio, it can be obtained if the vertical deformation is observed as well as the horizontal deformation (46). Schmidt also comments that the above equation should apply reasonably well if the loading time is short enough so that viscous effects are small. Under this assumption, the apparent modulus of elasticity E of a viscoelastic material is defined as the resilient modulus.

2-6-3 The Creep Test

Bituminous mixtures are recognized as a viscoelastic material (2,47), where a viscoelastic material refers to a material which is viscous but also exhibits elastic properties and whose stress-strain characteristics are time-dependent.

The general problem of a viscoelastic material is to compute its response to applied stresses and strains. In solving such problems, a mechanical model is usually employed to describe the behavior of viscoelastic materials. The elastic mode of response is represented by elastic springs and the flow mechanism by dashpots (48,50). The springs and the dashpots may be combined in various ways to describe observed experimental behavior as accurately as possible.

Alfrey (48) classifies the most interesting special cases of the general problem as follows:

- (1) Constant stress or constant load
- (2) Constant deformation
- (3) Constant rate of deformation
- (4) Stress or strain varying sinusoidally with time

The solutions to these cases are given by Alfrey (48). These solutions may be used to estimate the unknown properties of a viscoelastic material in terms of constants relating to each dashpot or spring if stresses or strains are applied to the material in the same fashion as the

corresponding problem dictates. The first case corresponds to the creep test, the second the relaxation test, the third relates to the "stress-strain" curve establishment with a constant crosshead speed testing machine such as in the Marshall stability test, and the fourth is the basis for determining a complex modulus from the dynamic modulus test (50).

The creep test consists of applying a constant force to a specimen and observing the deformation as a function of time (49). Within domain of asphalt paving technologists, the creep test has often been utilized. The work by Wood and Goetz (2) is one of the early investigations on the viscoelastic character of a sand-asphalt mixture. They applied static loads (ranging from 10 psi (0.7 kg/cm) to 375 psi (26.4 kg/cm) depending upon the temperature) to specimens 2 in. (5.08cm) in diameter and 4 in. (10.2cm) in height and the resulting deformation was observed with a dial gage. The observed behavior was explained by employing the Burgers model, a four element model with two springs and two dashpots. A simplification was made, however, to describe the behavior. The instantaneous elastic strain or rebound divided by the applied stress was named the Modulus of Recovery and the stress multiplied by the reciprocal of the slope of each time-deformation curve in the region where the deformation rate appeared constant over a period of time was called the

Mixture Viscosity. They found that the modulus of recovery and the mixture viscosity are independent of the applied stress and that the two factors may be used in understanding the action of a bituminous mixture under load. Linear relationships were found between log log modulus of recovery and temperature, between log log viscosity of mixture and temperature, and between log log viscosity of mixture and log log viscosity of asphalt.

Moavenzadeh and Sendze (51) applied creep and the relaxation tests to measure the effect of aging of sand asphalt mixtures. Specimens $1 \frac{3}{8}$ in. (3.49cm) in diameter and $2 \frac{7}{8}$ in. (7.30cm) in height, were placed in a triaxial test apparatus with water at 77 F (25 C) circulated around the test cell. Deformation was recorded by means of an LVDT (Linear Variable Differential Transformer) transducer connected to a recorder. Three levels of axial load on creep test specimens were applied, namely, 74.0 psi (5.2 kg/cm), 7.4 psi (0.52 kg/cm) and 3.75 psi (0.263 kg/cm). The amount of deformation allowed on the sample was limited to 0.03 in. (0.076cm) in practice. Samples were artificially aged in ovens at three levels of temperature, 77 F (25 C), 140 F (60 C) and 225 F (107 C) for one week. The modulus of recovery and the mixture viscosity, as defined by Wood and Goetz (2), were calculated from the creep curves, and it was found that the modulus of recovery could not be used as a practical parameter for aging

measurements due to the practical difficulty of finding the correct value of rebound, while the mixture viscosity values showed a more promising trend. Within the limit of observation, it was observed that the log of the mixture viscosity versus aging temperature generated a straight line, which might relate the mixture viscosity to the degree of aging. Though the Burgers model was used as the basis of analysis because of its simplicity, non-linearity was noted sometimes in their observed results. Pagen and Ku (52) employed the creep test in their investigation to relate changes of asphalt viscosity caused by temperature change to changes in the mechanical properties of bituminous mixture. Test specimens, 4 in. (10.2cm) in diameter and 8 in. high (20.3cm), were subjected to three levels of temperature, 41 F (5 C), 77 F (25 C) and 104 F (40 C) and three levels of axial stress for each level of temperature. A one hour loading and equal unloading duration were adopted. Their research indicated that the mechanical response of asphaltic concrete mixtures can be approximately described by the linear viscoelastic theory. In determining the equation of state, they used two methods; curve-fitting procedures for a generalized Voigt model, and a computer program in the form of sixth-degree polynomials.

A similar investigation has been conducted by Krokosky et al (53). Their results indicate, however, that the asphalt-aggregate composite generally show non-linear

viscoelastic behavior, and even behavior which is not viscoelastic. The departures from viscoelastic behavior appear to be associated with interparticle contacts of the aggregate. They conclude that there is no satisfactory theory at the present which would allow an adequate description of the interparticle effect.

Kumar and Goetz (54) employed the creep test in their study on asphalt hardening in asphalt mixtures. Because only the quantity of asphalt in contact with air in asphaltic concrete is oxidized in the weathering process and because the usual procedure of extracting asphalt will yield an average value of the affected and unaffected asphalt, a non-destructive compression creep test was found to be effective in their procedure. Specimens 4 in. (10.2cm) in diameter and about 2.3 to 2.7 inches (5.8 to 6.9cm) height were subjected to a cyclic loading for mechanical conditioning and then to a testing load of 5 psi (0.35 kg/cm) for 5 minutes. The axial deformation was sensed by two LVDT's connected to a recorder. The same specimens were subjected to the creep test repeatedly each time after a treatment of oxidation. The changes in slope and intercept values of the creep curves (log strain versus log time plots) were utilized as a measure of asphalt hardening. It was found the creep test can be employed as a non-destructive means for measuring progressive asphalt hardening in asphaltic mixtures.

Since each investigator utilized his own sample sizes, general conclusions may be difficult to develop from those articles. Pagen (55) utilized the creep test to determine the effect of sizes of specimens in the thermorheological sense. He justifies his choice of test since it was easily conducted with standard laboratory equipment, and yielded data over a wide range of the time scale and that the data obtained in the time domain could be transformed to the frequency domain for additional analyses. Specimens of 4-in. (10.2cm) in diameter but with different lengths were subjected to several levels of axial stress, ranging from 1.75 psi (0.12 kg/cm^2) to 21 psi (1.48 kg/cm^2), at three different temperatures, 41 F (5 C), 77 F (25 C) and 104 F (140 C). The axial and the radial deformations of specimens were measured using LVDT's connected to a recorder. The data indicated that both the linear viscoelastic theory and time-temperature superposition concept are applicable as engineering approximations to asphaltic concrete materials of varying Length/Diameter ratios. Further the time-L/D ratio equivalency, analogous to the time-temperature equivalence principle, was shown to be valid.

The quoted literature has dealt mainly with characterizing bituminous mixtures, but efforts have also been made to relate the viscoelastic behavior of the mixtures to a better understanding of flexible pavements (e.g. 47,56).

The investigators incorporated viscoelastic concepts into their design formulae. This development did not result in a simple approach. Though such research efforts will not be cited here, the possibility of relating the results of observation of viscoelastic properties of mixtures to design criteria for the pavement system should be retained.

CHAPTER 3

DESIGN OF EXPERIMENT

3-1 Framework of the Experiment

3-1-1 Scope

The basic objective of the experimentation in this study was to observe long-term behavior of cold processed recycling mixtures. The following items were determined before setting up the design of experiment:

- 1) Material procurement — The acquisition of pavement mixtures to be recycled, and softening agents.
- 2) Sample fabrication — The procedure for the fabrication and curing of samples.
- 3) Testing procedure — The mechanical property of the specimens to be evaluated, and the length of the testing period.

The three items were determined after referring to literature reviewed in Chapter 2.

3-1-2 Material Procurement

It was made clear in the literature review that in field practices the motivation of executing recycling

depends upon various factors and that there is no general rule for claiming a certain pavement section as being a representative one that would be encountered in practice. This means there is no predetermined level of consistency of asphalt in mixtures to be recycled. This causes difficulty in selecting "appropriate" pavement mixes to be recycled in a laboratory study.

It was decided that guidelines should be sought through field experiences in which deterioration of pavement is attributed to the hardening phenomenon of asphalt. Though literature is cited in a later chapter, it was found that the penetration of 30 dmm is the most convenient consistency level to represent mixtures to be recycled. In order to control this level of consistency, it was decided that mixtures should be obtained by artificially weathering virgin mixtures instead of sampling existing highways. This also helped in lessening the variation in observation caused by the variation in properties of excavated mixtures themselves. With respect to the method of artificial weathering, two methods were conceivable. The first type is to have bituminous mixtures weathered with their bituminous content reduced beforehand by some predetermined amount, and after weathering, a softening agent is added to produce the optimum binder content before compaction. The second type is to have bituminous mixtures weathered with their optimum bituminous content and then a softening agent, and

aggregate, if any, added. The first type is based on a hypothetical concept that severely aged asphalt contains a high amount of asphaltenes functioning as inert fines (15). It was determined, therefore, to use both techniques in order to decide which one to employ.

Any gradation might be used as the gradation of the original mixture in this study, since any course of a pavement could be recycled. A surface course, however, is always laid for an asphaltic pavement. Thus a surface course gradation was considered to be the most appropriate to investigate. A most typical gradation for a hot asphalt surface mixture designated No. 11 B in the Indiana State Highway Standard Specifications (57) was chosen. An asphalt cement designated as an AP-3 (57) with a penetration range of 85-100 was deemed to be typical and used in the investigation. A limestone was selected as the typical aggregate.

Softening agents were found to be always required to restore old pavement materials. The literature indicates asphalt cements, emulsified asphalts, cutback asphalts and various oils including rejuvenating agents are used in practice and in laboratory studies. However it must be borne in mind that, in laboratory studies, rejuvenating agents are used chiefly in hot processes, and very seldom in cold processes. In this study, an asphalt emulsion designated as AE-150 was selected to be used chiefly because

it was reported by Tia et al (22) to provide maximum asphalt softening of these agents used. Later on, other materials, AE-300, AC-2.5, and two rejuvenating agents Reclamite and Mobilsol were incorporated, because the literature review indicated they could be considered representing possible softening agents often utilized in practice.

3-1-3 Levels of Softening Agent Content to Add

The literature reviewed previously mentioned that there are three methods to determine the levels of softening agent to add to old mixtures, namely;

- 1) The amount of an agent is selected which yields a certain consistency level on the blending chart.
- 2) The optimum asphalt content of a virgin binder is determined by a conventional mix design.
- 3) The amount of the rejuvenating agent is selected by means of the blending chart, and the amount of a virgin binder is to be selected by a conventional mix design.

The first method is generally used when commercially available rejuvenating agents are to be incorporated. The second method is used with asphalt cements, emulsified asphalts, and cutback asphalts in most cases. The third method is only applicable for the combination of two agents.

In this research, it was decided to use the second method for AE-150, AE-300, and AC-2.5, while the amounts

of Reclamite and Mobilsol would be determined with the blending charts. Taking into account the fact that the original asphalt cement, AP-3, has the absolute viscosity of around 1000 poises, it was decided to retain that level of consistency in incorporating Mobilsol and Reclamite. This means that the oxidized asphalt cement inside a mixture is expected to be reclaimed to the original consistency.

3-1-4 Sample Fabrication

As will be discussed in the next section, it was decided to measure the creep behavior of the mixes. Since it was found that any sample size may be allowed in observing the creep behavior (55), a standard sample size of 4 inches (10.2cm) in diameter and about 2.5 inches (6.35cm) in height was employed. This size is not only convenient to fabricate but also may help to correlate the creep behavior with conventional design parameters. Possible ways to fabricate specimens are the Hveem, the Marshall and the Gyratory compactors. Considering the fact that the Hveem Method of mix design is specifically used in the Indiana State Highway Commission, it was decided to use the Hveem Kneading Compactor. Though a problem in using this compactor with recycled mixes was reported (21), it was possible to prevent build-up by heating the foot to about 140 F (60 C).

3-1-5 Aging After Recycling

With respect to the aging method after recycling, it was considered to be most appropriate to leave the specimens under the atmosphere of the laboratory because this may represent an average atmosphere pavement mixture will experience in the field. In the meanwhile, aging at higher temperatures may be of importance from the standpoint of accelerated test conditions. Thus it was decided to incorporate other temperature levels into the experiment.

Since this is a long-term observation program, it was determined to observe the specimens principally for six months.

3-1-6 Evaluation of Mechanical Properties

There are generally two ways to fulfill the purpose of this study to understand the changes of viscosities of binders. One is to fabricate many specimens and to run consistency tests on extracted binders at specified ages. Another is to run a non-destructive test which would yield certain mechanical properties, so that the changes of viscosities of binders could be estimated. A selection can be made when the merits and the demerits of the two are compared. The former may have an advantage by giving very accurate results. However, it may be expensive and time consuming. The latter, though it may not be as accurate, has an advantage over the former. Since one

specimen is to be continually observed throughout the period, an economy in time and labor to prepare specimens, and a reduction of variation inherent to specimens should be taken into account. Furthermore when the practical situation in highways is visualized, one would realize that it is the same pavement material that changes with aging. Thus considered, a non-destructive method is more intrinsic than direct measurement by extraction. The quoted literature indicates only two non-destructive procedures, the resilient modulus test and the creep test. Comparison between the two was made and it was decided to use the creep test in this study. The reasoning follows:

- 1) The resilient modulus is based on the theory of elasticity, and is not directly related to the viscosity of bituminous materials inside the mixture, even though some relationships are raised (24-25).
- 2) The creep test is fundamentally based upon the theory of viscoelasticity and the fact that a relationship between the viscosity of the mixture and the viscosity of bituminous material is reported to exist (2). In previous work (23,25) creep compliances observed for the recycled mixtures were not analyzed in the viscoelastic sense. However, preliminary work performed in this study indicated that a viscoelastic analysis of the creep test can be very useful in

describing the behavior more clearly. Therefore, such analysis was used in this study to interpret the results.

- 3) The primary interest in this study was to observe the change of viscosity of binders through the viscosity of the mixture. Thus it can be concluded that the creep test should be the better of the two tests.

It must be noted that in the cited literature no efforts were found that correlated the results of the long-term observations with design aspects. This fact makes it interesting to correlate long-term observations in terms of conventional design parameters if possible. Though the Hveem stability values were ruled out due to their lack in repeatability (21-22), it should be possible to measure the stability at the conclusion of the creep test to have some correlation between the stability and the initial creep behavior.

3-2 Sequence of Experiment

The experiment consisted of three stages, the preliminary, the first and the second stages.

In the preliminary stage, the mix design for the original mixture to be artificially weathered and recycled, establishment of the artificial weathering procedure, and preparation and preliminary work for the creep test procedure were completed.

In the first stage, four series of specimens were observed. One of the series contained specimens fabricated from the original mixtures without any agent, and they were intended to be used as a basis of comparison with other specimens. The second series contained specimens of recycled mixtures, which were recycled by adding certain amounts of AE-150 to the original mixtures that were oxidized to the level of penetration of 30 with the optimum asphalt content. The third series was the same as the second with virgin aggregate added. The fourth series also used a recycled mixture whose original asphalt content was reduced by certain amounts before being oxidized at 140 F for 15 hours. This procedure reduced the asphalt to a pen level of 60. AE-150 was added to make the optimum asphalt content. The reason for the different oxidation level is that reducing the asphalt content beforehand was thought to be equivalent to reducing the inert part of asphaltenes from the mixture. This is to say that, if the mixture with less asphalt content than the optimum were oxidized to the level of penetration of 30, the resultant mixture would have more inert portions than the mixture at the pen of 30 with the optimum asphalt content.

On the basis of information obtained during the first stage, some decisions were made and the second stage was begun. This stage consisted of eight series. Four of the series contained different softening agents,

i.e., AE-300, AC-2.5, Reclamite and Mobilsol. The other four series were aged at higher temperatures.

Details are discussed in each chapter.

CHAPTER 4

MATERIALS AND ORIGINAL MIXTURE PREPARATION

4-1 Scope

This chapter describes the materials used for this investigation, their sources and properties. It also presents the procedure used for fabricating the original mixtures. Recycling procedures are presented in the next chapter.

4-2 Mineral Aggregate

Aggregate used throughout this investigation consisted of limestone obtained from the Erie Stone Company of Huntington, Indiana. This aggregate is the same one employed by Khosla in his study (58) and it has been stored in the Purdue Bituminous Materials Laboratory. The mineralogical information is found in his final report (58). Specific gravity and absorption were measured in accordance with the ASTM Standard C127 and C128 and the results are shown in Table 1.

4-3 Bituminous Materials

4-3-1 Original Mixture

The bituminous material used for the original mixture was an asphalt cement with penetration of 85 to 100, which

Table 1 Specific Gravities and Absorptions of Aggregate (58)

Size Fraction	G_{BULK}	G_{BSSD}	G_{APP}	% ABS.
Coarse Aggregate	2.602	2.648	2.725	1.72
Fine Aggregate	2.749	2.778	2.831	1.05
Filler	-	-	2.809	-

is designated as AP-3 in the Indiana State Highway Standard Specifications (57). The asphalt cement was obtained from the Amoco Oil Company, Whiting, Indiana. Table 2 presents the physical properties.

4-3-2 Softening Agents

The materials used as softening agents were five in number; two of them were high-float anionic type asphalt emulsions designated as AE-150 and AE-300, respectively (57). They were formulated and provided by the K. E. McConnaughay Laboratory, Lafayette, Indiana. Their properties are shown in Table 3. A soft grade of asphalt designated as AC-2.5 was also used in the study. It was provided by Amoco Oil Company. Table 4 describes the physical properties. Two rejuvenating agents were used, and they are Mobilsol and Reclamite. They were kindly provided by the K. E. McConnaughay Laboratory, Lafayette, Indiana. Their properties are presented in Table 5. The results of chemical analysis were obtained from the research of Anderson et al (25).

4-4 Aggregate Gradation

As is stated in Chapter 3 the gradation for a hot asphalt surface mixture designated No. 11-B in the Indiana State Highway Standard Specifications (57) was chosen. The same gradation was used throughout the study. Even when virgin aggregate was to be added, the same gradation

Table 2 Physical Properties of AP-3

Test Property	Standard	Value
Penetration (100 gms, 5 sec, 25°C), dmm	ASTM D5	92
Specific Gravity (25°C)	ASTM D70	1.026
Ductility (5 cm/min, 25°C), cm	ASTM D113	100 ⁺
Absolute Viscosity (60°C, #11 Viscometer), poise	ASTM D2171	1010

Table 3 Physical Properties of AE-150 and AE-300

Test Property	Standard	Values	
		AE-150	AE-300
Saybolt Furol Viscosity (25°C), sec	ASTM D88	85	240
Distillate Percent by Weight, %	ASTM D244	27	27
Oil Portion of Distillate, %	ASTM D244	1.5	3.7
Tests on Distillation Residue	ASTM D244		
Penetration (100 gms, 5 sec, 25°C) dmm	ASTM D5	215	300
Specific Gravity (25°C)	ASTM D70	1.010	1.012
Distillate Percent by Weight, %	Evaporation*	27	27

* One hundred (100) gms of the emulsified asphalt in a 10000 ml beaker was heated up to 120°C with a direct flame.

Table 4 Physical Properties of AC-2.5

Test Property	Standard	Value
Penetration (100 gms, 5 sec, 25°C), dmm	ASTM D5	350 ⁺
Specific Gravity (25°C)	ASTM D70	1.024
Ductility (5 cm/min, 25°C), cm	ASTM D113	Incomplete*
Absolute Viscosity (60°C, #11 Viscometer), poise	ASTM D2171	300

* The asphalt was so soft that the shape of the specimen distorted when it was removed from the mold. Three specimens broke at about 70 cm, probably due to distorted shapes of the cross section.

Table 5 Physical Properties of Mobilsol and Reclamite

Test Property	Standard	Values	
		Mobilsol	Reclamite
Saybolt Furol Viscosity (25°C), sec	ASTM D88	69	25
Specific Gravity			
After Evaporation* (25°C)	ASTM D70	0.974	0.966
Distillate Percent by Weight, %	Evaporation*	28	37
Chemical Analysis**		Mobilsol [†]	Reclamite [‡]
Asphaltenes, %		Tr	0.5
Polar Compounds, %		17.1	17.7
1st Acidaffins, %		16.0	16.4
2nd Acidaffins, %		39.5	38.6
Saturates, %		27.5	26.8

* See Footnote, Table 3 [†] Same as Whitco Cycle-Pave in Base Form

** After Anderson et al (25) [‡] Base

was applied. The gradation is presented in Figure 3 and Table 6.

4-5 Mixture Design

The optimum asphalt content for the original mixture using AP-3 was determined by the Hveem Method following the Asphalt Institute Manual, MS-2 (59). The Swell Test was eliminated from the procedure, however.

The estimated asphalt content was determined by means of the Centrifuge Kerosene Equivalent Method (CKE Method) and the necessary data for the design charts and the design constants read from the charts are shown in Table 7. The method gave the estimated optimum asphalt content of 5.1 percent by the weight of dry aggregate.

Mixtures were fabricated using the estimated optimum asphalt content with alternate samples 0.5 percent below, and with 0.5, 1.0 and 1.5 percent above. Stabilometer values were determined for each specimen and the bulk density was determined following ASTM D2726, Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens. The summary of mixture properties is presented in Table 8. In the calculation of the percent voids, the maximum specific gravity of mixture was calculated using the bulk specific gravities of aggregate (59) instead of determined by ASTM D2041, Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures. The data indicates that the Stabilometer values obtained are

Table 6 Aggregate Gradation

Sieve Size	Percent ISHC # 11-B	Passing Mix
1/2 inch (12.5 mm)	100	100
3/8 inch (9.5 mm)	85-98	91.5
No. 4* (4.75 mm)	52 + 2	52
No. 8 (2.36 mm)	30-57	43.5
No. 16 (1.18 mm)	20-46	33
No. 30 (0.6 mm)	8-30	19
No. 50 (0.3 mm)	2-19	10.5
No. 100 (0.15 mm)	0-9	4.5
No. 200 (0.075 mm)	0-4	2

* Job-Mix Formula

FIGURE 3 AGGREGATE GRADATION

Table 7 Design Values

Item	Value
Surface Area ft ² /lb (m ² /kg)	19.1 (3.91)
CKE, %	2.00
CKE Corrected, %	2.14
Surface Capacity (Oil Retained), %	3.60
Oil Retained, Corrected, %	3.70
Surface Constants	
K _f	1.03
K _c	1.58
K _m	1.22
Oil Ratio, (%)	3.5
Corrected Oil Ratio, (%)	5.1 *

* By Weight of Dry Aggregate

Table 8 Summary of Mixture Properties

Property/Specimen	1	2	3	4	5
Percent Asphalt by Wt. Aggregate	4.6	5.1	5.6	6.1	6.6
Mix Bulk Sp. Gr.	2.350	2.366	2.381	2.405	2.406
Maximum Sp. Gr.	2.501	2.484	2.467	2.451	2.435
Air Voids, %	6.04	4.75	3.49	1.88	1.19
Stabilometer Value S	49	45	43	41	40

all above the required design criterion for the heavy traffic section, while the percent air voids is not satisfied by the specimens with the asphalt content of 5.6% and above. Therefore, the asphalt content which satisfies the minimum requirement of the air voids of 4% was determined to be the optimum. Thus the optimum asphalt content was decided to be 5.4% by weight of dry aggregate, or 5.1% by weight of total mixture.

4-6 Artificial Weathering of Mixtures

4-6-1 Scope

In order to obtain artificially aged mixtures to be recycled, a study was made with respect to the method and the degree of weathering. Discussed here are the literature review for methods and the degree of weathering, experimental procedures and the result.

4-6-2 Literature Review

There have been several procedures devised to artificially weather asphalt mixtures. In their study on the effect of degree of aging on creep and relaxation behavior of sand-asphalt mixtures, Moavenzadeh and Sendze (51) employed the method of aging loose mixtures in electric ovens in the presence of air for one week at three different temperatures: 77 F (25 C), 140 F (60 C) and 225 F (107 C).

Kumar and Goetz, in their study (54), subjected compacted specimens to repeated oxidation by passing air

through them in an oven maintained at 140 F (60 C) for 24 hours after each observation of the creep behavior. Tia et al (22) oxidized pavement material under heat at 250 F (121 C) for one day and three days.

It is a routine procedure to subject a loose mixture to the heat of 140 F (60 C) for 15 hours before fabricating specimens for the Hveem Method of mix design (59). Although some other weathering methods such as infrared or ultraviolet weathering are suggested (51), the literature indicates that high temperature weathering is mainly employed in most studies.

As is quoted in Chapter 2, there are many factors which cause hardening of asphalt. Heating is one of them. Heating causes chain scission, and cross-linking and furthermore stimulates volatilization of the oily part of the asphalt. The factor that is more predominant may depend on the nature of the asphalt. It might be expected that volatilization of oils in asphalt would be accelerated rather than oxidation if the asphalt mixture is exposed to higher temperature than atmospheric temperature. Thus the high temperature weathering might produce weathered mixtures different from mixtures aged under ambient conditions. So far, however, no extensive research has been done in this respect, and it was decided to weather mixtures artificially at high temperatures.

Following the question as to the method of artificial weathering, the next question arises regarding the degree

of weathering. Practical experiences of recycling as was shown in Chapter 2, however, indicate that the levels of hardening of asphalt prior to recycling vary in both penetration and viscosity. This is because of the fact that the motivation for recycling usually depends upon other reasons than that upon the deterioration of pavement due to weathering. This leads to the conclusion that the experience from actual jobs does not always give the answer to this particular problem. Next sought were the references concerning the relationship between the deterioration of pavement and the consistency of asphalt in it. Observations at the Zaca-Wigmore Asphalt Test Road (60) indicate that penetration of 30 is approximately the critical consistency for the failure criterion adopted for the project for fatigue type cracking. Investigation of crack distribution made in the Meishin Expressway (61), the first expressway in Japan, shows that, when the penetration of the recovered asphalt becomes less than 50, hair cracks and alligator type cracks were found at some sections, and when the penetration reaches 30, all the sections showed alligator type cracks. The cracks are considered to have been caused not by the shortage of bearing capacity of embankment and/or bases but by the deterioration of the mixtures (62). Bright et al (63) also note that the cracking of the pavement usually occurs when penetration values fall below 30. These references suggest that the penetration of 30 dmm is a guideline of deteriorated mixture, when

the deterioration of pavement is spoken of in terms of the properties of bituminous mixtures. This leads to the conclusion that a penetration of 30 may be employed as the degree of weathering of mixtures to be used in a study of recycling.

4-6-3 Experimental Procedure

The purpose of this experiment was to find the correlation between the hardening of asphalt in mixture and the duration and temperature of artificial weathering in an oven. As indices of hardening of asphalt, it was decided to measure the penetration value and absolute viscosity with the asphalt extracted from artificially weathered mixtures.

The duration and temperature of artificial weathering were based on the literature review. The conditions used are shown in Table 9. The procedure used was as follows:

- 1) 1500 gms of aggregate and AP-3 asphalt were heated to 300 F (148.9 C) (59) and then mixed with an electric mixer. The asphalt content was the optimum content as previously determined.
- 2) The mixture was transferred to a pan, 11 inches (28cm) X 7 inches (18cm), 1.5 inches (4cm) deep, and cured in a forced-draft oven for the duration and at the temperature stated in Table 9. (The electric oven used for the curing was Model #1412 made by the Electric Hotpack Company, Inc.)

Table 9 Levels and Results of Artificial Weathering

Weathering Duration	Condition Temperature (F) (C)	Penetration (100 gms, 5 sec, 25 C) dmm	Extracted Asphalt Absolute Viscosity (60 c) Poise
0 hrs	- -	66	1410
15 hrs	140 (60)	63	1953
15 hrs	250 (121)	28	21,560
1 day	250 (121)	24	58,390
2 days	250 (121)	11	Aprx. 2,600,000

- 3) After the curing, extraction of asphalt was made according to Method A, ASTM D2172, Quantitative Extraction of Bitumen from Bituminous Paving Mixtures, followed by ASTM D1856, Recovery of Asphalt from Solution by Abson Method. The sample to be weathered for 0 hrs duration was extracted immediately after mixing.
- 4) Penetration and absolute viscosity tests were performed on the recovered asphalt according to ASTM D5, Penetration of Bituminous, and ASTM D2171, Viscosity of Asphalt by Vacuum Capillary Viscometer, respectively.

4-6-4 Results

The results are shown in Table 9.

Since the original asphalt had a penetration of 92 and an absolute viscosity of 1010 poises, a large change in penetration was observed due to the mixing with aggregate. However, weathering at 140 F (60 C) for 15 hours causes a comparatively small change in penetration after the original drop due to mixing. Drastic change is observed in both penetration and absolute viscosity when the mixture is exposed to heat at 250 F (120 C) compared with the mixture at 140 F (60).

As a penetration level of 30 was to be employed in this study, it was decided that weathering for 15 hours at 250 F (60 C) should be applied to the original mixtures.

CHAPTER 5

LABORATORY RECYCLING PROCEDURES

5-1 Scope

This section describes the procedure used in the laboratory to recycle the artificially weathered bituminous mixtures. The procedure includes specimen preparation and the initial tests on the specimens. The creep test procedure is discussed in Chapter 6.

5-2 Specimen Preparation Procedure

All the softening agents used in this study, except for AC-2.5, are in the form of a emulsion. Therefore the basic procedure followed was for cold mix emulsion mixtures. There are several mix design procedures proposed (64), but in order to be consistent in evaluating cold processes recycling, the procedure used by Tia et al (22) was used in this study. The procedure was originally developed by Gadallah in his Ph.D. thesis (26). The procedure employed in the work being reported was as follows:

- (1) The artificially weathered original mixture in a loose condition was cooled in the room temperature for about 4 hours. While it was still hot, and after it had become cool, the mixture was loosened repeatedly

- by vigorously stirring by hand with a spoon.
- 2) One percent of water by the weight of total original mixture was added and mixed thoroughly by hand with a spoon, and left for 10-15 minutes.
 - 3) The predetermined amount of emulsion kept at the room temperature was added and mixed for the first 30 seconds with a mechanical mixer, for additional 30 seconds by hand, and for one minute with the mixer again.
 - 4) The mix was cured for one hour in a forced-draft oven at 140 F (60 C).
 - 5) The mix was remixed for 30 seconds with the mechanical mixer, and the mix was then ready for compaction.

The purpose of adding water was to facilitate the mixing process, and in the field to prevent dusting. Before deciding to incorporate the one percent level, a comparison was made and the level of one percent of water was found just enough to wet the old mixture.

Hand mixing for 30 seconds was found necessary, otherwise larger chunks in the old mixture sometimes tended to stick to each other and segregation took place. This phenomenon was seen especially when AE-150 was applied. With other emulsions, this was seldom observed.

The above procedure was sometimes modified depending upon the agent used. These modifications are noted when they occur.

The procedure for AC-2.5 was almost the same with the exception of adding water. The AC-2.5 was heated to 350 F (177 C) and then poured into the old mixture at room temperature and two minute mixing was begun immediately.

5-3 Compaction

The Hveem Kneading Compactor was used to compact the specimens. The sequence follows:

- 6) The compactor foot was preheated to about 140 F (60 C) to prevent the mix from adhering to it (64).
- 7) Immediately after remixing, one-half of the mix was transferred to a mold and rodded 20 times in the center and 20 times around the edge. The same procedure was repeated after the remainder was transferred.
- 8) The mold assembly was placed on the mechanical compactor and one minute tamping, about 30 tamps, was applied at 250 psi (17.5 kg/cm^2) pressure.
- 9) After the semi-compaction, the shim was removed and the mold allowed to act freely. Compaction for 5 minutes, i.e. about 150 tamps was then applied at 500 psi (35.2 kg/cm^2).
- 10) After the compaction, the specimen was levelled with the maximum load of 1000 psi (70.3 kg/cm^2) by the double plunger method, with a head speed of 0.05 in per minute (0.02 mm/s).

- 11) Thirty minutes after the compaction, the specimen was extruded from the mold and kept at room temperature.

5-4 Initial Tests

After one day curing at room atmosphere, the Hveem stability, and creep behavior tests were run. In the Hveem stability test, both the R values and the S values were measured at the room temperature instead of at 140 F (60 C). The procedure followed the Asphalt Institute Manual (59). About one hour later, the creep test was conducted, and the weight and the height were measured. With some specimens, the specific gravity was measured according to ASTM D2726, Standard Test Method for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens. When this test was run, the specimens were dried almost to the original weight by an electric fan.

After these tests, specimens were kept on shelves in the laboratory at the room temperature. The specimens destined to be cured at high temperatures were kept in two forced-draft ovens.

CHAPTER 6

CREEP TEST AND ANALYSIS METHOD

6-1 Scope

As mentioned in Chapter 3, the creep test was chosen as the means for observing long-term behavior. The creep test basically consists of applying a force to a specimen and maintaining it constant. The deformation is measured as a function of the time. This chapter presents the equipment used in this study, the testing procedure, a mathematical model for analysis, and some results of preliminary work.

6-2 Equipment

The equipment used in this study is almost the same as that used by Kumar and Goetz (54). It consists of a loading frame, a means for loading and unloading a specimen, a pressure gauge for measuring load, and a recorder. A general view of the equipment is shown in Figure 4.

The load was applied with a double-acting type air cylinder using compressed air. Two LVDT's were used to sense the axial deformation of the specimen. They were placed equi-distant from the central axis of the specimen and directly opposite to each other in order to obtain

an average value of the axial deformation. A specimen and the LVDT holder assembly is shown in Figure 5.

The LVDT's were connected directly to the Texas Instruments Oscillo-riter with two channels. A carrier amplifier was used for each channel of the recorder. Calibration of the LVDT's was done by displacing the core with a micrometer and recording the displacement. The magnitude of the pen deflections was adjusted so that 0.001 inches displacement in the core corresponded to 1 cm in the recording chart at the attenuation of X100. The attenuation was changed to the position of X40 for the usual observation. The recording chart was rectilinear and graduated in 1.0mm; thus it was possible to read the displacement on the chart to the precision of 0.1mm approximately.

The entire testing was carried out at room temperature (average: 69.5 F (20.8 C), the standard deviation: 2.1 F (1.2 C)).

6-3 Testing Procedure

The creep test procedure used in this work was based upon a preliminary study as explained later in this chapter.

- 1) A specimen was mounted in the loading frame, and the head of aluminum alloy, weighing 3 lb. (1364 gm) was placed over the specimen. The head was used to support the lower end of the LVDT's. Sometimes silicon grease

FIGURE 4 EQUIPMENT FOR
THE CREEP TEST

FIGURE 5 A SPECIMEN AND
THE LVDT HOLDER ASSEMBLY

has been applied or a rubber pad put between the specimen and the equipment to avoid barreling (65), but in this study they were not used. It was feared that silicon grease might damage the surfaces of specimens in the long run, and the rubber pad was found to affect the observed values especially in the modulus of elasticity term.

- 2) The specimen was subjected to repeated cycles of loading and unloading. The load was 10 psi (0.70 kg/cm^2) in magnitude and was applied for 30 seconds followed by 30 seconds of an unloading period. This procedure is referred to as "mechanical conditioning" (52,54-55).
- 3) The specimen was left in the frame with the head on it for 10 minutes and 30 seconds, and then subjected to the test loading of 5 psi (0.35 kg/cm^2) in magnitude for 5 minutes. The recorder speed was set at 0.5mm/second, and was used to record the deformation caused by this test loading (5 psi).
- 4) The specimen was taken from the frame and then returned to the shelf or the oven for the specific period of aging.
- 5) The chart record was read every 10 seconds beginning with 10 seconds up to 120 seconds. After this, it was read every 60 seconds up to 300 seconds. Since the output was obtained for two sides, left side and right side from the LVDT's, these values were averaged, and divided

by the height times the stress (5 psi), and a factor of attenuation. The results were key-punched as a set of input data to the SPSS NONLINEAR regression analysis program in the Purdue University Computing Center.

A typical chart record is shown in Figure 6, and the deformation reproduced through the regression analysis is shown in Figure 7. (The specimen represented in Figures 6 and 7 is the same.)

6-4 Mathematical Model for Analysis

6-4-1. Linear Viscoelasticity

Linear viscoelasticity deals with a viscoelastic material such that if the stress is doubled, the resultant strain will also be doubled at a given loading time interval (66). The response of such a material may be mechanically represented by a combination of linear elastic springs and linear viscous dashpots. In a linear elastic spring, the deformation between its two ends is proportional to the applied force, and in a linear viscous dashpot, the sides move apart at a rate proportional to the applied force (49).

The statement above can be formulated in mathematical forms (49) as:

$$\text{in a spring} \quad \sigma = E \epsilon \quad (6-1)$$

$$\text{in a dashpot} \quad \sigma = \eta \frac{d\epsilon}{dt} = \eta \dot{\epsilon} = \eta D\epsilon \quad (6-2)$$

FIGURE 6 A TYPICAL CHART RECORD
OF DEFORMATION WITH TIME

FIGURE 7 A TYPICAL CREEP COMPLIANCE CURVE

where σ is stress, ϵ is strain, E is the spring constant or the modulus of elasticity, and η is the viscosity constant. D denotes differentiation with respect to time t .

The elastic spring is called the Hookean body and the dashpot the Newtonian body (66).

6-4-2 The Maxwell Model and the Kelvin Model (32,49,66-67)

In linear viscoelasticity, the two basic elements, the Hookean and the Newtonian bodies, are combined to describe mechanical behavior of actual viscoelastic materials. When the two bodies are combined in series, the combination is called the Maxwell Model, and when combined in parallel, it is called the Voigt or Kelvin or Kelvin-Voigt Model, as are illustrated in Figure 8.

In the Maxwell Model, the stress should be equal in the two elements. Then,

$$\sigma = E \epsilon_s = \eta D \epsilon_d \quad (6-3)$$

where the subscripts s and d refer to the spring element and the dashpot element respectively. The total elongation of the two elements, or the strain in the unit basis, is given by

$$\epsilon = \epsilon_s + \epsilon_d \quad (6-4)$$

Taking the derivative with respect to time t in Eq. (6-4),

(A) MAXWELL
MODEL

(B) VOIGT
MODEL

(C) BURGERS
MODEL

FIGURE 8 SOME OF VISCOELASTIC MODELS

$$D\epsilon = \left(\frac{1}{E} D + \frac{1}{\eta}\right) \sigma \quad (6-5)$$

Eq. (6-5) is the constitutive equation of the Maxwell Model.

In the Voigt Model, a similar procedure can be used and the constitutive equation is given by

$$\sigma = (E + \eta D) \epsilon \quad (6-6)$$

6-4-3 Creep Compliance

The objective of conducting the creep test is to find a stress-strain relationship for a certain mathematical model under the condition that the specimen is subjected to a constant stress σ_0 at time $t=0$. This condition, or the boundary condition, is formulated in an equation using the Heaviside unit function $H(t)$, as follows (49,67):

$$\sigma(t) = \sigma_0 H(t) \quad (6-7)$$

where the Heaviside unit function $H(t)$ is defined (68) by

$$H(t) = \begin{cases} 1 & 0 < t \\ 0 & t < 0 \end{cases} \quad (6-8)$$

when $t=0$, $H(0)$ is sometimes defined as $1/2$. This may be extended to define at any time t , as:

$$H(t-t_1) = \begin{cases} 1 & t_1 < t \\ 0 & t < t_1 \end{cases} \quad (6-9)$$

The strain in the creep test is observed as a function of time after loading σ_0 . When the function of strain, $\epsilon(t)$, is divided by the constant stress σ_0 , it is called the creep compliance (66) denoted $J(t)$, or

$$J(t) = \epsilon(t)/\sigma_0 \quad (6-10)$$

The formulae of $J(t)$ for several models are given below:

For the Hookean element;

$$J(t) = H(t)/E$$

$$\text{or} \quad J(t) = 1/E \quad (t > 0) \quad (6-11)$$

For the Newtonian element, Eq. (6-2) gives

$$D \epsilon(t) = \sigma/\eta = \sigma_0 H(t)/\eta$$

On integration,

$$J(t) = H(t) t/\eta$$

$$\text{or} \quad J(t) = t/\eta \quad (t > 0) \quad (6-12)$$

For the Maxwell Model, Eq. (6-5) gives

$$D \epsilon(t) = \left(\frac{1}{E} D + \frac{1}{\eta} \right) \sigma_0 H(t)$$

On integration,

$$J(t) = 1/E + (1/\eta) t \quad (t > 0) \quad (6-13)$$

And for the Voigt Model, Eq. (6-6) gives

$$(E + D) \eta(t) = \sigma_0 H(t)$$

Solving the nonhomogeneous ordinary differential equation,

$$J(t) = (1/E) \{1 - \exp(-\frac{E}{\eta} t)\} \quad (6-14)$$

6-4-4 The Burgers Model

The Burgers Model consists of a Voigt unit and a Maxwell unit in series as is illustrated in Figure 8.

The constitutive equation for the Burgers Model can be derived in a similar fashion as is done with the Maxwell Model, and is given by

$$[D^2 + \frac{1}{\tau} D] \epsilon = \frac{1}{E_1} [D^2 + (\frac{1}{\tau_1} + \frac{1}{\tau_2}) D + \frac{1}{\tau_1 \tau_2}] \sigma \quad (6-15)$$

where τ , τ_1 , τ_2 are defined by

$$\left. \begin{aligned} \tau &= \eta_2 / E_2 \\ \frac{1}{\tau_1} + \frac{1}{\tau_2} &= \frac{E_2}{\eta_2} + \frac{E_1}{\eta_2} + \frac{E_1}{\eta_3} \\ \frac{1}{\tau_1} \cdot \frac{1}{\tau_2} &= (E_1 E_2) / (\eta_2 \eta_3) \end{aligned} \right\} \quad (6-16)$$

E_1 : the modulus of elasticity of the Maxwell unit

η_3 : the viscosity of the Maxwell unit

E_2 : the modulus of elasticity of the Voigt unit

η_2 : the viscosity of the Voigt unit

τ : the retardation time

The creep compliance $J(t)$ is calculated as;

$$J(t) = \frac{1}{E_1} + \frac{1}{E_2} [1 - \exp(-t/\tau)] + t/\eta_3 \quad (6-17)$$

A general form of the creep compliance for the Burgers Model is shown in Figure 9.

It would be possible to construct more complicated models combining more Voigt units and Maxwell units. When the Voigt unit in the Burgers model is replaced by series of several (or infinite number of) Voigt units, the model is called the generalized Voigt Model. When a Newtonian unit, a Hookean unit and several (or infinite number of) Maxwell units are all connected in parallel, the model is called the generalized Maxwell Model (49).

In this study, the Burgers Model was determined to be used in the analysis because of the following reasons:

- 1) The Burgers Model is commonly used in many references and has been shown that this model can describe viscoelastic behavior of bituminous mixtures fairly well.
- 2) Interpretation of the four elements of the Burgers Model is possible, while it becomes more difficult with the models with more elements.
- 3) The procedure in this study includes estimation of the constant values for the elements by means of a curve fitting method. The more sophisticated the model becomes, the more difficult and expensive the analysis becomes. Since a large number of samples were expected to be observed, it was not practical to use more sophisticated models.

The next step was to investigate the general shape of the creep behavior of the Burgers Model. The summary follows:

- 1) The initial response of the model upon application of the constant stress σ_0 is given by

$$\epsilon(0^+) = \lim_{t \rightarrow 0^+} \epsilon(t) = \sigma_0 / E_1$$

$$\text{or} \quad J(0^+) = 1/E_1 \quad (6-18)$$

That is, the instantaneous increase in the creep compliance $J(t)$ equals the elastic rebound governed by E_1 . This means that E_1 is identical to the modulus of recovery defined by Wood and Goetz (2).

- 2) The creep compliance $J(t)$ has an asymptotic line $f(t)$ given by

$$f(t) = \left(\frac{1}{E_1} + \frac{1}{E_2} \right) + t/\eta_3 \quad (6-19)$$

Eq. (6-19) indicates that the creep compliance curve has the slope of $1/\eta_3$ when t reaches infinity. This means that η_3 is identical to the mixture viscosity defined by Wood and Goetz (2). Comparison of Eq. (6-19) with Eq. (6-13) yields a conclusion that they are identical when $\frac{1}{E_1} + \frac{1}{E_2}$ in Eq. (6-19) is replaced with $1/E$. This indicates that the asymptotic line given by Eq. (6-19) corresponds to

the creep compliance of the Maxwell Model when the half of the harmonic mean of E_1 and E_2 is taken as the modulus of elasticity E of the Maxwell Model, or in an equation form,

$$E = \frac{1}{2} E_H \quad (6-20)$$

$$E_H = \frac{2}{\frac{1}{E_1} + \frac{1}{E_2}} \quad (6-21)$$

Where E_H is the harmonic mean of E_1 and E_2 .

- 3) When the constant stress σ_0 is instantaneously removed from the specimen at time t_1 , the creep recovery takes place. If the Boltzman superposition principle (66) is assumed, the creep compliance $J_r(t)$ after the removal of the stress is given by

$$J_r(t) = J(t) - J(t-t_1) \quad (t > t_1) \quad (6-22)$$

or

$$J_r(t) = \frac{1}{E_1} \left\{ \exp\left(\frac{t_1-t}{\tau}\right) - \exp\left(\frac{-t}{\tau}\right) \right\} + \frac{t_1}{\eta_3} \quad (t > t_1) \quad (6-23)$$

- 4) The instantaneous creep recovery is given by

$$J(t^-) - J_r(t_1^+) = 1/E_1 \quad (6-24)$$

This means the instantaneous recovery is equal to the instantaneous increase upon loading.

- 5) When the time t approaches infinity, $J_r(t)$ approaches t_1/η_3 or,

$$J_r(t) \rightarrow t_1/\eta_3 \quad (t \rightarrow \infty) \quad (6-25)$$

This indicates that the strain never recovers to the initial value but the permanent deformation remains. The permanent deformation is greater as the time elapse of loading is longer and the viscosity is smaller.

- 6) Behavior of τ may be interpreted when the creep compliance $J(t)$ is plotted with different values of τ keeping other parameters, E_1 , E_2 and η_3 , constant. The creep compliance curve in dotted lines in Figure 9 is a curve with a higher τ value than the curve in the solid line. Then it can be concluded that τ is related to the time when the creep compliance curve reaches the asymptotic line. The higher the value of τ , the slower is the approach to the asymptotic line. That is to say, a bituminous material with a higher τ value has a longer transitional region if other parameters, E_1 , E_2 and η_3 are kept constant.

All these properties are presented in Figure 9.

6-5 Curve Fitting Method

6-5-1 Literature Review

As is stated in Chapter 3, the creep test was used to evaluate changes in viscosity of binders as reflected in

FIGURE 9 GENERAL FORM OF
THE BURGERS MODEL

changes in viscosity of mixtures. To obtain the viscosity of the mixture, the constants of a suitable mathematical model must be obtained from the data of each observation. The fundamental idea of obtaining the values of the constants lies in curve fitting. Several methods have been developed in the literature, which will be briefly reviewed.

Wood and Goetz (2) obtained their modulus of recovery and mixture viscosity from the time-deformation curve by reading the instantaneous elastic rebound at time zero and the slope of the curve where the deformation rate was apparently constant over a time period. The inverse of the rebound in unit stress is taken as the modulus of recovery, and the inverse of the slope in unit stress is taken as the mixture viscosity. Since the curves are plotted on linear scales, the modulus of recovery is equal to E_1 , and the viscosity of mixture is equal to η_3 in the Burgers Model. They did not discuss the retardation time τ nor the second modulus of elasticity E_2 .

Kumar and Goetz (54) used a graphical method, but the curves were plotted on log scales. The intercept value of the creep curve was arbitrarily taken at 1 second, and the creep curve slope value was read from the curves. Since the curves are plotted on log scales, this procedure is not based on linear viscoelastic formulae, but on a different relationship called logarithmic creep (55,68) in which the strain ϵ is assumed to be proportional to log of creep time t .

Moavenzadeh and Sendze (51) calculated the rebound modulus and the mixture viscosity in the same way as Wood and Goetz. They also calculated the four constants of the Burgers Model for some observed results, but the method they used is not known and they did not utilize the calculated four constants to explain the creep behavior any further. They refer to the difficulty in determining exactly where the instantaneous rebound ends and the retarded rebound begins on the recorder chart. For this reason, they conclude that the modulus of recovery could not be used as a practical parameter for aging measurements.

Pagen and Ku (52) used a generalized Voigt model with eight Voigt units and calculated the constants by using a graphical procedure, which is not explained in their paper. They also calculated similar equations of a sixth degree polynomial form using a computer.

As has been seen so far, graphical procedures seem to have been preferred, probably due to the simplicity in handling. It should be pointed out, however, that graphical procedures can give only the two values at most, the intercept and the slope. Other constants, e.g., η_2 and E_2 in the Burgers Model might be valuable in the analysis of aging effect in this study, but the above procedures do not easily give these values. This requires different procedures from graphical ones. Numakura (69) explains a statistical procedure to determine the four constants, a , b , c , and d , in an experimental equation,

$$y = a + bx + ce^{dx} \quad (6-26)$$

The independent variable x is assumed to be taken equi-distant. The basic idea lies in taking the first and the second differences between the adjacent observed values and solving for the four constants analytically. Though this method is complicated in handling, this could yield the four values required. This method was tried in actuality with some observed results in this study, and the following points were found:

- 1) Though this is peculiar to this study, the second differences are found to be almost only of one digit. This means that the accuracy of the resultant constant values may be of that order.
- 2) This method may be a modification of a statistical procedure. The modification was required in the past because such a sophisticated method as the least square method was too complicated to apply to nonlinear systems like Eq. (6-26).

The above discussion necessitates reviewing other statistical procedures using modern computer programs. It was found that SPSS, the Statistical Package for the Social Sciences, contains a nonlinear regression analysis program (71-72), which is discussed in the next section.

6-5-2 Nonlinear Regression Analysis Method

Though Eq. (6-17) for the Burgers Model is linear with respect to the stress, it is not linear with respect to the variable and with respect to the four constants, or the parameters. Eq. (6-14) may be rewritten in the following form;

$$J(t, B) = B_1 + B_2 \{1 - \exp(-B_3 t)\} + B_4 t \quad (6-27)$$

Where $B = (B_1, B_2, B_3, B_4)$ is a vector of the parameters. In mathematical terms, the nonlinear regression analysis consists of minimizing the sum-of-squares function which is given by:

$$S(B) = \sum_{i=1}^n [J'_i - J_i(t, B)]^2 \quad (6-28)$$

Where J'_i is the i^{th} observed value and n is the number of observations.

The SPSS NONLINEAR allows the user to select one of two minimization techniques, Gauss method or Marquardt's method. In this study the Gauss method was used. For further information about the procedure the following reference (72) should be examined.

A computer program used in this study is presented in Appendix A.

The output was obtained in the form of $B = (B_1, B_2, B_3, B_4)$, and the four constants were calculated as the inverse of B , as follows:

$$\left. \begin{aligned} E_1 &= 1/B_1 \\ E_2 &= 1/B_2 \\ \tau &= 1/B_3 \\ \eta_3 &= 1/B_4 \end{aligned} \right\} \quad (6-29)$$

The second constant of viscosity, η_2 , can be calculated by Eq. (6-30):

$$\eta_2 = \tau E_2 \quad (6-30)$$

The advantage in using the SPSS NONLINEAR Program in lieu of graphical procedures can be summarized as follows:

- 1) Since the least square method is utilized to compute the four parameters, the obtained values are more reliable in general than these obtained by graphical procedures.
- 2) With respect to E_1 , or the modulus of recovery, a difficulty claimed by Moavenzadeh and Sendze that the instantaneous rebound cannot be determined exactly is eliminated. Graphical procedures utilize only one observed value to obtain the modulus of recovery, while the computer program uses all the observed values resulting in much more accuracy.
- 3) As is shown in the next section, it is sometimes difficult to determine where the creep compliance curve has a constant slope, which means η_3 or the mixture viscosity is also difficult to determine. This can also be solved by using the computer program because of the same reason given above.

Caution must be taken, however, with the program. The program requires as input the estimated values of the parameters. If the estimates are wrong, the program can sometimes yield quite different results such as negative values in E_1 , η_3 , etc. These kinds of errors can be checked by means of the plotting of residuals and the magnitude of the root mean square of residuals provided by the computer, but there still remains a basic problem that there is no guarantee of the existence of a unique solution.

6-6 Preliminary Study

6-6-1 Scope

This section describes several experiments concerning the creep test procedure and the creep behavior of the specimens. As is described in 6-3, two phases of the creep test procedure are based on the preliminary experiments. The necessity and the conditions of the mechanical conditioning are discussed first, and the duration of loading is discussed secondly. Next follows the discussion on the validity of the linear viscoelasticity using the data in the creep recovery region of the creep compliance curve. It is the basic idea in this study that the hardening in asphalt affects the creep behavior of asphalt mixtures. To obtain a general trend of the creep behavior with the progress of weathering, an experiment was made, which is discussed next. Since the same specimens are tested repeatedly in the creep test, repetition of loading might

damage the specimens. To know the effects of observation frequency another experiment was done. This will be described in the last paragraph.

6-6-2 Mechanical Conditioning

Pagen and Ku (52) reported that after three or four cyclic loadings their bituminous material seemed to follow the linear viscoelastic assumption to a higher degree of approximation. The cyclic loading is called the mechanical conditioning. Based on this observation, Kumar and Goetz (54) applied 10 cycles of loading and unloading as the mechanical conditioning after which a continuous load was applied and the creep behavior was observed.

Moavenzadeh and Sendze (51) stated that the creep curves they obtained for the specimens under the first application of load had a very high initial value of instantaneous deformation, far larger than the elastic rebound. They attributed this to initial compression of the specimens.

Though the discussion by Pagen and Ku that the bituminous material seems to follow the linear viscoelastic assumption after three or four cyclic loadings may be questionable in terms of linear viscoelasticity, the fact reported by Moavenzadeh and Sendze was also observed in a preliminary phase in this study. One possible cause of this phenomenon may be the unevenness of the surfaces of a specimen which require one or two impacts of loading

to get complete contact with the surfaces of the head and the base of the loading assembly. The observation in this study, therefore, also necessitates mechanical conditioning as a preliminary to testing. Though Kumar and Goetz (54) applied 10 cycles of loading with the magnitude of 5 psi (0.35 kg/cm^2) and one minute of unloading, it was decided to apply a different cycle in this study as is described in 6-3 taking the economy in observation time into account.

After the mechanical conditioning, the specimen was left unloaded for 10 minutes and 30 seconds. The unloading period is necessary to erase the memory effect which is caused by loading in the mechanical conditioning. The 10 minutes duration was determined based on the experimental observation that the rate of increase in the deformation of specimens is seemingly zero at around 7 or 8 minutes after unloading. This was confirmed by means of a calculation using the retardation time of about 35 seconds.

6-6-3 Loading Time

Since the creep test was to be conducted repeatedly with many samples, the factor of loading time was critical. It was observed, however, that it took a long loading period for the creep curve to seemingly reach the linear region. A longer loading time, however, would cause larger permanent deformation in the specimens and they might be damaged. Taking this into consideration, the optimum

loading time should be determined.

An experiment was conducted in which six specimens (#4 series, to be discussed in Chapter 8) were prepared, each two of them having the same asphalt content, i.e., OAC (optimum asphalt content), OAC-1%, and OAC+1%. When the specimens were one day old, the first creep test was performed. After mechanical conditioning, the load of 5 psi (0.35 kg/cm^2) was applied to each specimen for 15 minutes. The four constants of the Burgers Model were calculated with the computer for the loading period of 5 minutes, 10 minutes and 15 minutes.

The four constants were plotted against loading time in Figure 10, (A), (B), (C), and (D). The following are now clear:

- 1) E_1 and E_2 decrease and η_3 increases, as loading time increases.
- 2) τ , the retardation time, is not a constant, but increases and becomes more variable at longer loading times.

The values of the root mean square residuals are also plotted in Figure 10(E). This plot indicates the root mean square residuals increase as the time increases. Since the root mean square residuals is an estimate of the standard deviation, this fact means that accuracy of prediction decreases as the time increases. That is, the shorter the loading time, the more precise are the estimated

FIGURE 10 EFFECTS OF LOADING TIME

constants. This may be counter to the concept that the more precise results should be obtained with longer observation periods. The contradiction can be resolved when a creep compliance curve is presented as an example. Figure 11 is a typical curve which shows that, even at longer time, the curve still cannot be taken as linear. This fact reminds one of the observations in Figure 10(C) that τ increases as time passes. If the specimens were to obey the Burgers Model, the four constants should be unchanged. The reason this is not true may lie on the fact that τ is actually not a constant but is a function of time. This suggests that the Burgers Model is not effective in describing the creep behavior for longer loading periods, but that more complex models, such as a generalized Voigt Model should be used and τ should be described as a functional form called the retardation spectrum (32,66). Employing such a higher model, however, does not necessarily fit with the purpose of this study.

A shorter loading time could be suggested, but, as Figure 11 depicts, only the transitional portion is observed if a shorter loading time is used, and inaccurate results will be obtained.

It was concluded, then, that the loading time should be 5 minutes from the standpoint of the validity of the Burgers Model. The loading time of 5 minutes is also desirable with respect to avoiding damage to specimens.

FIGURE 11 CREEP COMPLIANCE FOR 15MIN. LOADING

The permanent deformation is proportional to the loading period as is indicated by Eq. (6-25) in 6-4-4. When η_3 is taken as 4×10^7 psi·sec, the permanent deformation per observation including the effect of the mechanical conditioning is 7.5×10^{-5} in/in, and if 50 observations should be taken, the total deformation is about 0.4 percent. If the loading time is 15 minutes the total deformation is doubled and reaches the critical limit of one percent deformation, beyond which the linear range is said to be exceeded (73), and the specimens may be damaged.

6-6-4 Creep Recovery

Though the recovery part of the creep behavior is not important in this study, it should be mentioned from the viewpoint of linearity.

The creep recovery was observed with several specimens in the #4 series and the curve for one of them is presented in Figure 7. The black circles depict the observed values and the solid line is the calculated creep compliance using the four constants obtained through the non-linear regression analysis with the data of the creep region only. If the Boltzman superposition principle should hold with this specimen, the solid line should pass through the black circles in the creep recovery region as well as the creep region. This was found not to be true with Figure 7, though the trends of the circles and the solid line are similar.

The constants were calculated in the recovery region by means of the non-linear regression analysis based on Eq. (6-23), and the following observations were made:

- 1) E_2 and η_3 are smaller in the recovery region than in the creep region.
- 2) τ is much longer (about 3 times) in the recovery region as well as the creep region.
- 3) E_1 cannot be calculated from Eq. (6-23).

These observations indicate that the Boltzman superposition principle does not hold in the strict sense. Since the Boltzman principle is an extension of the principle of linearity, the above discussion means that linearity does not hold exactly. The Burgers Model may still be used, however, if the four parameters are to be calculated from the data in the creep region under strictly controlled loading conditions.

6-6-5 Effects of Oxidation on Creep Behavior

As is described in Figure 1 schematically, asphalt mixtures are spontaneously oxidized by aging and become harder with time. It is the fundamental concept in this study that the hardening affects the creep behavior of asphalt mixtures. Therefore it was considered to be valuable to know the changes in the creep behavior of the mixtures artificially weathered in an oven.

It was decided to conduct an experiment at the same time the method of artificial weathering of mixtures was evaluated as described in 4-6. The procedure of the experiment was the same as is explained in 4-6-3, except for the weight of aggregate, which was 1200 gm instead of 1500 gm. The mixtures were subjected to the artificial weathering condition shown in Table 9, and then they were compacted according to the standard Hveem Mix Design Method (59). On the day following compaction, the creep test was conducted on each specimen.

The calculated values of the Burgers Model parameters for this series, designated as #3 series, are presented in Table 10. In the table, the penetration and the absolute viscosity values are entered again from Table 9. To express quantitatively the level of heating for a certain period, an index, called the Weathering Index (WI), is arbitrarily defined as follows:

$$WI = T \times H \quad (6-31)$$

where T is the temperature difference in degrees centigrade between the temperature applied to the mixture and the room temperature and H is the heating period in hours. T is given by

$$T = (5/9) (t - t_p) \quad (6-32)$$

where t is the oven temperature in degrees Fahrenheit and t_o is the room temperature, 70 F. The WI values are

Table 10. Effects of Oxidation on Creep Behavior

Sample	3-6	3-5	3-7	3-4	3-1
Weathering Condition					
Hours	0	15	15	24	48
Temperature, F (C)	-	140 (60)	250 (121)	250 (121)	250 (121)
WI, Hr C	0	583	1500	2400	4800
Creep Parameters					
E_1 , psi	12640	15050	18120	20920	22550
E_2 , psi	33180	32390	42120	41930	90170
η_2 , psi·sec, $\times 10^6$	1.289	1.312	2.093	1.192	2.958
η_3 , psi·sec, $\times 10^7$	0.917	0.935	1.026	1.030	2.712
τ , sec	38.85	40.52	49.68	28.44	32.81
E_H , psi	18310	20550	25340	27920	36080
Consistency of Extracted Asphalt					
Penetration (100 grms, 5 sec, 25 C), dmm	66	63	28	24	11
Absolute Viscosity (60 C), poise	1426	1953	21562	58391	Approx. 2600000

entered in Table 10. It must be kept in mind that the index WI is not an absolute property but quite arbitrary. Several plottings were attempted between the observed values, and the following observations were made:

- 1) In general, all the creep parameters except τ showed an increase in their values as the weathering index (WI) increased, though a few exceptional values exist.
- 2) The retardation time τ fluctuated and no general trend could be seen.
- 3) Among the parameters, the harmonic modulus of elasticity (E_H) showed linearity against WI as shown in Figure 12 (A). The others showed non-linear relationships.
- 4) Linear relationships were found in the following combinations of values:
 - (1) Between log of absolute viscosity and log of penetration of extracted asphalt
 - (2) Between log of absolute viscosity of extracted asphalt and WI
 - (3) Between log of penetration of extracted asphalt and WI
- 5) A functional relationship was found between $\log \log \eta_3$ and $\log \log$ absolute viscosity of extracted asphalt as it is shown in Figure 12 (B), but it is not a linear one.

The above observations suggest the existence of linear relationships between E_H and log of absolute viscosity, and between E_H and log of penetration. Regression equations for the linear relationships were computed and shown below:

$$\left. \begin{aligned} \log \text{ Penetration} &= 2.679 - 4.61 \times 10^{-5} E_H \quad (R = -0.989) \\ \log \text{ Abs. Viscosity} &= -0.469 + 1.90 \times 10^{-4} E_H \quad (R = 0.997) \\ \log \text{ Abs. Viscosity} &= 10.45 - 4.05 \times \log \text{ Pen.} \quad (R = -0.991) \end{aligned} \right\} \quad (6-33)$$

where R is the correlation coefficient.

The second viscosity η_3 is identical to the mixture viscosity defined by Wood and Goetz (2). They showed a linear relationship between log log viscosity of asphalt and log log viscosity of sand asphalt mixture. Figure 12 (B) shows different results, though linearity seems to hold within certain limits. It must be noted however, that the absolute viscosity of the mixture after 48 hours of oxidation at 250 F (121.1 C) is suspect because it was too large to be measured with the vacuum capillary viscometer described in ASTM D2171, Standard Test Method for Viscosity of Asphalt by Vacuum Capillary Viscometer. Thus further discussion should be suspended. Nevertheless, Figure 12 (B) still indicate the existence of a functional relation between the two variables.

Though the results in this experiment indicate that the creep behavior is affected by oxidation and that continuous relationships exist between most parameters and the

(A)

(B)

FIGURE 12 EFFECTS OF
ARTIFICIAL WEATHERING

levels of oxidation, care must be taken in using the results, especially quantitatively. As will be discussed in later chapters, most specimens show a rapid decrease in the creep compliance as the age increases, while the results obtained here were the initial observation values. Secondly, the mixtures in this experiment were weathered in a loose condition before compaction. These conditions of weathering and compaction are different from specimens under long-term observation. Therefore the results should be considered to be only applicable to initial observation values of any specimens when they are to be compared with #3 series used here.

In conclusion to this section, the observation of #3 series initially indicates that not only the viscosity of mixture η_3 but also the moduli of elasticity E_1 , E_2 and E_H are affected by oxidation and that their values increase as the level of oxidation increases. Therefore these parameters may be utilized equally as indices of oxidation.

6-6-6 Effects of Observation Frequency

Since the same specimens are to be tested repeatedly in the creep test, repetition of loading could cause specimens to consolidate which in turn might cause a change in creep behavior. Such an effect is natural in the actual situation of the pavement under traffic flow, but with the laboratory specimens, a different problem may occur. If repeated loading should cause a significant

change in creep behavior, a specimen subjected to the creep test everyday may decrease in creep compliance more rapidly than another specimen subjected to the test every four days (or five days or whichever). Based on this consideration, a test on two specimens was made.

The two specimens were made by the hot process with the optimum asphalt content. After one day curing in the room atmosphere, both were subjected to the initial creep test and kept at room temperature. One specimen, denoted Sample 5-1, was tested everyday and the other, Sample 5-2, was tested every four days. The test condition was almost the same as is described in 6-3.

Figure 13 (A) depicts the relation between the creep compliance at 10 sec., 60 sec., and 300 sec. versus the age in days up to 21 days. The solid lines are for Sample 5-1 and the dotted lines are for Sample 5-2. The figure indicates the following:

- 1) The creep compliance generally decreases with time.
- 2) The two specimens show almost the same trend with the age, though Sample 5-1 shows a steep decrease in the compliance during the first two days.

To investigate the change of the two specimens, the five parameters of the Burgers model were calculated and are presented in Figure 13 (B), (C), (D), (E) and (F). They indicate the following:

FIGURE 13 CREEP BEHAVIOR OF
 SAMPLES 5-1 AND 5-2

FIGURE 13 CONT.

FIGURE 13 CONT.

- 3) E_1 , E_2 and η_3 are increasing as the age increases, however, τ , the retardation time, is almost constant.
- 4) Samples 5-1 and 5-2 show almost parallel relationships in E_1 , E_2 , η_3 and τ except the initial observation of 5-1.

The observed trends in 1) and 3) above suggests that the specimens are increasing in hardness with age, while the retardation time is found to be unchanged during the aging process. The fact that the two specimens show almost parallel relationships may indicate that the loading frequency does not affect the creep behavior. With respect to the initial rapid change found with Sample 5-1, the loading frequency could be presumed to affect the creep behavior, but there is no evidence to judge whether it is true or not. As will be shown in later chapters, this type of phenomenon was sometimes experienced with two equally fabricated specimens under equal loading conditions. One such pair showed high values of the creep compliance which decreased rapidly in a few days, while the other pair showed low values of the creep compliance from the very beginning, and the long term trends were found to be almost equal. This fact suggests that specimens show erratic behavior during the first few days after fabrication, probably because of slight differences in material properties or in handling of materials during sample fabrication or other reasons, even though all the specimens

were leveled off with the load of 1000 psi (70.3 kg/cm^2).

Based on the observation and discussion above, it may be concluded that difference in testing frequency do not produce significant effects on specimen creep behavior in the long-run.

6.7 Summary

The investigation reported in this chapter indicates the following points:

- 1) The Burgers Model can describe the viscoelastic character of bituminous mixtures fairly well when it is analyzed by means of non-linear regression analysis.
- 2) The Burgers Model can be applied to analyze the creep behavior, but non-linearity is found in the creep recovery region. Therefore restrictions should be made so as to use only the creep region data.
- 3) The loading time of 5 minutes in the creep test was found appropriate from the standpoint of the validity of the Burgers Model.
- 4) Artificial weathering causes increases in values of creep parameters E_1 , E_2 , E_H , η_3 and η_3 , in monotonic fashion.
- 5) The loading interval does not have a significant effect on the creep behavior of specimens.

Based on the summary above, it may be concluded that the creep test can be used as the tool in this study when it is analyzed with the Burgers Model through the non-linear regression analysis. Though the basic parameters of the Burgers Model are four in number, other derived parameters such as the retardation time τ and the harmonic mean of the moduli of elasticity, E_H , may be of some use in the analysis. Therefore six parameters, E_1 , E_2 , η_2 , η_3 , τ and E_H , are used in the following investigations. These parameters are referred to as the creep parameters hereafter.

CHAPTER 7

BLENDING CURVE

7-1 Scope

The basis of recycling is the application of a softer material to the aged asphalt in an old mixture to reestablish ductility, viscosity, penetration, etc., to a certain level. Solution may take place upon the application, resulting in a blend of the two materials. This is only a simplification of the concept since there is no reason of the blend being homogeneous, and further discussion is required as to whether this concept is applicable or not to the cold recycling processes. Nevertheless, this blending concept has been developed and used conventionally to predict the amount of rejuvenating agents to be added to old mixtures under the implicit assumption that the resulting blend is homogeneous.

The original purpose of establishing blending curves in this study was to determine the appropriate amount of the rejuvenating agents, Mobilsol and Reclamite, using conventional procedures. In the course of experiments it was found that the blending curve concept was not applied to other materials. Thus a trial was made to

establish the blending curve for asphalt emulsions and asphalt cements.

The results through the experiment indicated that a functional relationship exists between the consistency and the concentration of all of the softening agents used in the experiment including AC-2.5, AE-150 and AE-300 as well as Mobilsol and Reclamite.

This chapter presents the experiment, the results and discussion.

7-2 Experiment

7-2-1 Scope

The purpose of the experiment was to establish the blending curves for Mobilsol, Reclamite, AE-150, AE-300, and AC-2.5. The old asphalt to be reclaimed was AP-3, which was weathered artificially to the level of a penetration of 30.

The whole structure of the experiment consisted of the following procedures:

- 1) Acquiring weathered asphalt
- 2) Preparing softening agents
- 3) Blending and curing
- 4) Performing penetration and viscosity tests
- 5) Analysis

Since the first procedure required special attention, it is discussed separately and the remaining procedures are then discussed as a whole procedure.

7-2-2 Acquisition of Weathered Asphalt

7-2-2-1 Method of Acquisition

The literature review in Chapter 2 showed that in establishing blending curves most researchers acquired asphalt by extraction from highway mixtures. This could not be applied in this study. The remaining ways were either extracting asphalt from artificially weathered mixtures as described in Chapter 4 or artificially weathering asphalt itself. The latter was employed simply because of convenience.

Literature was reviewed regarding to the methods of artificial weathering. There are many papers proposing the methods of weathering asphalt artificially. Among them, the study made by Escobar and Davidson (74) showed interesting results by comparing the field data with three ways of accelerated aging, and concluded that the hardening of asphalts by prolonged exposure in the RTFC oven and mild air blowing are reasonable approaches to simulate severe field hardening of asphalts. Based on their results, it was decided that heating of asphalt in a thin film in an oven should be employed in this study.

7-2-2-2 Determination of Heating Time Period

ASTM D1754-78, standard Test Method for Effect of Heat and Air on Asphaltic Materials (Thin-Film Oven Test), specifies that 50 ml of asphalt be exposed to heat at 325 F (162.8 C) for 5 hours. With this time period, however, the level of oxidation cannot be determined. Since the level of consistency of asphalt to be recycled was determined at the penetration value of 30, the time period necessary to attain the level should be determined. To do this, eight samples of AP-3, each in a pan, 5 1/2 in. in inside diameter and 3/8 in. deep, were prepared and put into the oven (same oven as described in Chapter 4), kept at 325 F with air circulated. The pans were not rotated but placed on a shelf in the oven. After predetermined time periods, each sample was poured into a 3 oz. can, cooled to the room temperature, and the penetration values were measured according to ASTM D5.

The results are shown in Table 11 and Figure 14.

From the results obtained above, it was decided that heating for 7 hours and 40 minutes is appropriate to achieve a penetration value of 30.

7-2-3 Procedure of Establishing Blending Curves

Since all the softening materials except for AC-2.5 were in an emulsified form, each material was evaporated following the procedure described in Chapter 4. In evaporating materials, distillate percentage was calculated

Table 11 Results of Prolonged Thin Film Oven Test

Time (hours)	Penetration (dmm)
3	51
4	46
5	40
6	36
7	32
8	29
9	28
10	24

FIGURE 14 RESULTS OF
PROLONGED T.F.O.T.

and whether or not the evaporation had finished completely was checked each time. AC-2.5 was prepared through the ordinary laboratory procedure.

The original asphalt, AP-3, was artificially weathered following the described procedure for 7 hours and 40 minutes. The samples were fabricated each time for each softening material. Penetration and absolute viscosity were measured for the first two cases to check the variation. It was found that the variation in consistency at different times of fabrication was rather small. The weathered asphalt was transferred into beakers and was cooled to room temperature.

Softening agents were poured into each beaker in the amount predetermined. The trial percentages of the softening agents were determined rather intuitively depending upon their own consistency.

Each combination of the weathered asphalt and a softening agent in a beaker was kept at room temperature for several hours for observation, but no reaction was seen to take place at room temperature as far as it could be detected by eye. After this, the beakers were transferred to an oven and kept there at 140 F (60 C) for one hour to simulate the procedure of fabrication of mixture specimens. After this exposure to heat, only the interface of the two materials (weathered asphalt and a softening agent) seemed to be softened a small amount, but no

drastic change was seen even with Mobilsol or Reclamite. After this observation, and while the specimens were still hot, vigorous mixing with a glass rod was possible for the samples with Mobilsol and Reclamite. However, mixing was difficult when AC-2.5, AE-150 and AE-300 were used.

The blends were kept at room temperature again for several hours. After this period, the samples with Mobilsol presented an interesting phenomenon. The sample with 10 percent of Mobilsol residue was stiff, while that with 40 percent of Mobilsol residue seemed to be stiff at first look, but became more fluid once it was stirred with a glass rod. This is called thixotropy (29,32) and this property is usually found with high-float type asphalts such as AE type asphalt emulsions. The specimen with a high amount of Reclamite showed a soft property and did not show the thixotropic character.

After several hours duration, the blends were transferred into an oven at 275 F (135 C). After about 15 minutes in the oven, the blends were completely mixed with glass rods. They were kept in the oven for another 5 minutes, then poured into appropriate viscometers and cans (3 oz. or 6 oz.). Absolute viscosity and penetration values were determined following ASTM D2171 and D5, respectively.

7-2-4 Experimental Results

The experimental results are shown in Table 12. In the table, concentration of softening materials is given both in percentage by weight of the weathered asphalt (AP-3) and in percentage by weight of the total blend. The relationship between the two percentages is given by the following simple equation:

$$p = \frac{100 q}{100 + q} \quad (\%) \quad (7-1)$$

$$\text{where } p = \frac{W_s}{W_s + W_a} \times 100 \quad (\%) \quad (7-2)$$

$$q = \frac{W_s}{W_a} \times 100 \quad (\%) \quad (7-3)$$

p: concentration of a softening agent in percent by weight of the total blend

q: concentration of a softening agent in percent by weight of the weathered asphalt

W_s : weight of softening agent in the blend

W_a : weight of weathered asphalt in the blend

7-3 Discussion of Results

7-3-1 Scope

Based on the experimental results shown, the possibility of developing of experimental equations to determine the concentrations of softening agents to restore to the aged asphalt to certain levels is discussed.

Table 12 Results of Blending

Softening Material	Concentration (%)		Absolute Viscosity (poise)	Penetration (dmm)
	by Weight of AP-3	by Weight of Total Blend		
Reclamite (Residue)	0.0	0.0	6855	30
	10.0	9.1	1401	71
	20.9	17.3	399	189
	40.0	28.6	113	-
Mobilsol (Residue)	0.0	0.0	6855	30
	10.0	9.1	1568	65
	20.0	16.7	527	146
	40.0	28.6	142	-
AE-300 (Residue)	0.0	0.0	6855	30
	20.3	16.9	999	98
	40.3	28.7	419	180
	60.9	37.8	239	-
	82.2	45.1	148	-
AE-150 (Residue)	0.0	0.0	6855	30
	20.0	16.7	2422	51
	40.2	28.7	1378	71
	60.4	37.7	962	94
	81.0	44.8	708	107
AC-2.5	0.0	0.0	6855	30
	10.0	9.1	4933	37
	20.0	16.7	3733	42
	40.0	28.6	2957	49
	150.0	60.0	851	124

7-3-2 Experimental Equations

In order to find the general relationship between the consistency and the concentration of softening agents, plots were made on a trial basis for the following combinations of variables shown in Table 13.

All of the combinations were plotted, and the combination of $\log(\log \eta)$ versus p and that of $\log(\text{Pen})$ versus p were found to present linearity. The graphs of those two combinations are shown in Figure 15 (A) and (B).

All the softening agents showed almost perfect linearity in the graph of $\log(\log \eta)$ versus p , regardless of the type of the softening agent. Therefore one form of experimental equation given by Eq. (7-4) may be applicable to all the agents:

$$\log(\log \eta) = A - Bp \quad (7-4)$$

where A and B are constants to be computed by means of linear regression analysis.

With respect to the graph of $\log(\text{Pen})$ versus p , similar relationship may be possible, though there seem to exist some deviations. An experimental equation is in the form of Eq. (7-5):

$$\log(\text{Pen}) = D + Ep \quad (7-5)$$

The values of the pairs of constants, A , B , and D , E are computed for all the agents and are shown in Table 14.

Table 13 Combinations of Variables for Plotting

Consistency	Ordinate	Abcissa
Absolute Viscosity, η	$\log \eta$	$q^{(*)}$
	$\log \eta$	$p^{(*)}$
	$\log(\log \eta)$	q
	$\log(\log \eta)$	p
Penetration, Pen	Pen	q
	$\log(\text{Pen})$	q
	$\log(\text{Pen})$	p

(*) p: concentration of a softening agent in percent by weight of the total blend. Given by Eq. (7-2)

q: concentration in percent by weight of the weathered asphalt. Given by Eq. (7-3)

(A) LOG LOG VISCOSITY VS P

FIGURE 15 BLENDING CURVES

(B) LOG PENETRATION VS P

FIGURE 15 CONT.

Table 14 Constants in Experimental Equations

Softening Agent	Eq. (7-4)			Eq. (7-5)		
	A	B	R	D	E	R (*)
Reclamite (Residue)	0.5834	0.009532	0.9998	1.462	0.04611	0.9978
Mobilsol (Residue)	0.5837	0.008798	0.9999	1.465	0.04101	0.9979
AE-300 (Residue)	0.5775	0.005408	0.9979	1.492	0.02734	0.9967
AE-150 (Residue)	0.5809	0.002852	0.9984	1.488	0.01251	0.9980
AC-2.5	0.5860	0.001901	0.9978	1.458	0.01015	0.9894

(*) R: Coefficient of Correlation

The physical interpretation of the constants A, B and D, E was next examined. When the concentration p is equal to zero, the consistency of the "blend" should be equal to that of the weathered asphalt, while it should be the consistency of the softening agent when p is equal to 100. Denoting η_0 and η_1 the viscosity of the weathered asphalt and that of the softening agent respectively, A and B are given by the following equations:

$$\begin{aligned} A &= \log(\log \eta_0) \\ B &= \frac{1}{100} \{ \log(\log \eta_0) - \log(\log \eta_1) \} \end{aligned} \quad (7-6)$$

In the same way, D and E are given by:

$$\begin{aligned} D &= \log(\text{Pen})_0 \\ E &= \frac{1}{100} \{ \log(\text{Pen})_1 - \log(\text{Pen})_0 \} \end{aligned} \quad (7-7)$$

Or inversely, η_0 and $(\text{Pen})_0$, the consistency of the weathered asphalt could be expressed as:

$$\begin{aligned} \eta_0 &= (10)^{10^A} \\ (\text{Pen})_0 &= 10^D \end{aligned} \quad (7-8)$$

Eqs. (7-6) and (7-7) indicate that all of the constants would be uniquely determined once two extreme values of consistency were determined. In actuality this is sometimes

impossible to do with some softening agents, because a penetration might not be measured as the agent is too soft, or the absolute viscosity might be lower than one poise, where $\log(\log \eta)$ is not defined as a real number.

Eq. (7-8) means that the consistency of the weathered asphalt is directly related to A and D. This is the reason why the entries in columns A and B in Table 13 are almost the same respectively, the deviation being caused by the observation error. This can be confirmed by calculating $\log(\log \eta_0)$ and $\log(\text{Pen})_0$, where $\eta_0 = 6855$ poise and $(\text{Pen})_0 = 30$ dmm as are found in Table 11.

The fact that all of the softening agents used in this experiment follow the same equation may mean that the same physico-chemical reaction is taking place in the blend irrespective of the nature of the softening material.

The results presented here seem to support the results obtained by Davidson et al (4) that there exists a linear relationship between $\log \log$ of the absolute viscosity and the weight percent of softening agent in the blend as was discussed in 2-5-4, while in terms of the penetration value, the results here suggest a different form from those discussed in 2-5-6. It is beyond the purpose of this study, and the limitation of the extent of this experiment, however, to discuss the blending curves in general terms. The conclusion on this point should wait for further investigation.

With the results obtained here, the following points should be borne in mind:

- 1) Only one kind and one level of weathered asphalt was used for blending with softening agents. Other types of asphalt may well present quite different blending curves.
- 2) The concentration p of the softening agent is limited to 45 percent except for AC-2.5, thus the relationships obtained above are valid to this extent in a strict sense.

7-3-3 Amount of Softening Agents to Restore the Weathered Asphalt

Since one of the purposes of softening agents is to reduce the consistency of a hardened asphalt to a certain level, the concentration of the agents to reach such a level should be determined. Further discussion should be made, however, as to what level should be employed. In this section, the amounts of softening agents were calculated to obtain several levels of consistency, using the regression equations given in the previous section.

The concentration p and q were calculated by the following formulae:

$$p = \frac{1}{B} \{A - \log(\log \eta)\}$$

$$p = \frac{1}{E} \{\log(\text{Pen}) - D\} \quad (7-9)$$

$$q = \frac{100 p}{100 - p}$$

As to the levels of consistency, it was decided to use the central values of the range of those asphalt cements specified by the Indiana State Highway Standard Specifications (57); AC-2.5, AC-5, AC-10, AC-20, AC-40; AP-6, AP-5, AP-4, AP-3, AP-2, AP-1, and AP-0. The calculated values are presented in Table 15. It must be noted that some results are calculated by extrapolation, i.e., some calculated values exceed the limits of the results of this experiment. Some values are used in proportioning the mixture in later chapters.

It is clear from Table 15 that some concentrations are irrational. For example, almost the same amount of AC-2.5 as the amount of the original asphalt would be required to restore the weathered asphalt to the AC-10 level, if AC-2.5 were to be used as a softening agent. This amount of AC-2.5 would be used to restore the weathered asphalt if the blending concept is followed. This is not practical however, because the added AC-2.5 acts also as an asphalt to aggregates, resulting in an increase in the total asphalt content. The same discussion may be applicable to other softening agents, even when the values in Table 15 are not large. Even the rejuvenating agents may act not only to soften old asphalts but also to add to the total asphalt content to some extent. This is argued in this way: some portion of maltenes (N fraction) in the original asphalt cement is believed to have converted to asphaltenes (A) during aging as is discussed in 2-4-3. The rejuvenating

Table 15 Concentration of Softening Agents to Restore the Weathered Asphalt to Various Grades

Asphalt Grade	Consistency	Reclamite*		Mobilsol*		AE-300*		AE-150*		AC-2.5	
		p %	q %	p %	q %	p %	q %	p %	q %	p %	q %
Viscosity Grade											
AC-2.5	250 poises	21.4	27.2	23.2	30.2	36.5	57.5	70.5	239.0	-	-
AC-5	500	16.0	19.0	17.3	20.9	27.1	37.2	52.5	110.5	81.4	437.6
AC-10	1000	11.1	12.5	12.1	13.8	18.6	22.9	36.4	57.2	57.3	134.2
AC-20	2000	6.8	7.3	7.4	8.0	10.9	12.2	21.8	27.9	35.4	54.8
AC-40	4000	2.8	2.9	3.1	3.2	3.9	4.1	8.5	9.3	15.5	18.3
Penetration Grade											
AP-6	55 dmm	6.0	6.4	6.7	7.2	9.1	10.0	20.2	25.3	27.8	38.5
AP-5	65	7.6	8.2	8.5	9.3	11.7	13.3	26.0	35.1	35.0	53.8
AP-4	77.5	9.3	10.3	10.3	11.5	14.5	17.0	32.1	47.3	42.5	73.9
AP-3	92.5	10.9	12.2	12.2	13.9	17.3	20.9	38.2	61.8	50.1	100.4
AP-2	110	12.6	14.4	14.1	16.4	20.1	25.2	44.2	79.2	57.5	135.5
AP-1	135	14.5	17.0	16.2	19.3	23.3	30.4	51.3	105.3	66.2	195.9
AP-0	175	16.9	20.3	19.0	23.5	27.5	37.9	60.4	152.5	77.3	340.5

* In residue

agent acts to redisperse the asphaltenes, which had increased in amount during aging. Thus the resultant blend contains more asphalt than the original asphalt did. The extent of increment in the asphalt may depend the dispersing ability of the agent and the degree of N portion converting to A.

The total asphalt content A_q in the mixture may be expressed as:

$$A_q = A_0 \left(1 + f \frac{q}{100} \right) \quad (7-10)$$

$$0 \leq f \leq 1$$

where A_0 is the concentration by percent weight of the original asphalt, and

f is the function of the dispersing ability of the agent and the degree of N fraction converting to A.

It is a fact that the increase of the total asphalt content is very important in the properties of mixtures, but the blending curve does not answer the question to what extent the total asphalt increases upon application of a softening agent. Only the average level of consistency of the blend is given. That is, the blending curve is not directly related to the mixture property. Therefore it must be pointed out that the blend should always be mixed with aggregate to check whether it gives the optimum mixture property or not. This means that determining the amount of a softening agent with the blending curve is not sufficient and the mixture property should always be

examined by means of a conventional mix design procedure, at least. When the blend is found not to give the optimum mixture property, some remedies to adjust the excessive asphalt, such as addition of virgin aggregate, should be taken.

7-4 Summary

Within the framework of the experiment, the following should be pointed out:

- 1) Blending curves can be constructed for asphalt cements and emulsified asphalts in addition to commercially available rejuvenators. The curves show no differences in the functional shape among the softening agents.
- 2) A linear relationship was found between log log of absolute viscosity and the concentration of a softening agent in total blend by weight, and between log of penetration and the concentration.
- 3) The blending curve was found not to be sufficient to determine the amount of softening agent to be used in a mixture and at least a conventional mixture index, such as the Hveem stability, should be examined. This is necessary because the addition of a softening agent may increase the total asphalt content; however, the extent of increase cannot be estimated easily since it is a function of the dispersing ability of the agent and the degree to what the N fraction converts to A fraction.

CHAPTER 8

TEST RESULTS - ORIGINAL MIXTURES AND AE-150

8-1 Scope

This chapter presents the experimental results for the four test series. The basic information is presented in Table 16.

The first series, designated as #4 series, contains specimens fabricated from the original mixtures without the addition of any agent. They were fabricated by the conventional Hveem Method (59) using the hot process. This series was intended to be used as a basis of comparison with other specimens.

The other series, designated as #6, #7, and #8 series, were recycled mixtures with AE-150.

The specimens in the #6 series contained the original mixtures with the optimum asphalt content. The mixtures were oxidized to the level of a penetration 30. The AE-150 was added using the cold process described in Chapter 5.

The #7 series used the original mixtures with the asphalt content reduced by certain amounts before being subjected to the artificial weathering at 140 F (60 C) for 15 hours. The penetration level of the extracted asphalt was about 60. This series had three sub-series, each

Table 16 Basic Information for #4, #6, #7 and #8 Series

Series	Specimen Notation	Original Mixture Oxidation Condition	Asphalt Content (%)	AE-150 (Residue) Added* (%)	Virgin Aggregate Added (%)	Total Asphalt Content* (%)	Concen- tration of AE-150 (Residual) *** P (%)	Calculated Blend Consistency	
								Viscosity (Poise)	Pen. (dmm)
4	4-1, 4-4	140°F, 15 hr	OAC**=1	0.0	0.0	4.4	0.0	1953	63
	4-2, 4-5		OAC	0.0	0.0	5.4	0.0	1953	63
	4-3, 4-6		OAC +1	0.0	0.0	6.4	0.0	1953	63
6	6-2, 6-4	250°F, 15 hr	OAC	0.5	0.0	5.9	8.5	4008	39
	6-3, 6-6			1.0	0.0	6.4	15.6	2747	48
	6-1, 6-5			1.5	0.0	6.9	21.7	2013	57
7A-F	7-A, 7-D	140°F, 15 hr	OAC	0.0	0.0	5.4	0.0	1953	63
	7-B, 7-E			0.5	0.0	5.9	8.5	1416	70
	7-C, 7-F			1.0	0.0	6.4	15.6	1094	76
7G-I	7-G, 7-J	140°F, 15 hr	OAC - 1	1.0	0.0	5.4	18.5	987	79
	7-H, 7-K			1.5	0.0	5.9	25.4	778	86
	7-I, 7-L			2.0	0.0	6.4	31.2	640	92
7M-R	7-M, 7-P	140°F, 15 hr	OAC - 2	2.0	0.0	5.4	37.0	530	99
	7-N, 7-Q			2.5	0.0	5.9	42.4	447	106
	7-O, 7-R			3.0	0.0	6.4	46.9	389	112
8A-F	8-A, 8-D	250°F, 15 hr	OAC	0.0	0.0	5.4	0.0	6453	31
	8-B, 8-E			0.5	0.0	5.9	8.5	4008	39
	8-C, 8-F			1.0	0.0	6.4	15.6	2747	48
8G-I	8-G, 8-J	250°F, 15 hr	OAC	1.34	25.0	5.4	24.9	1727	63
	8-H, 8-K			1.84	25.0	5.9	31.2	1270	76
	8-I, 8-L			2.34	25.0	6.4	36.6	990	88
8M-R	8-M, 8-P	250°F, 15 hr	OAC	2.68	50.0	5.4	49.6	563	128
	8-N, 8-Q			3.18	50.0	5.9	53.9	472	145
	8-O, 8-R			3.68	50.0	6.4	57.5	409	161

* Percent by Weight of Total Aggregate

** OAC-Optimum Asphalt Content, 5.4%

*** Percent by Weight of Total Blend

of which used a different level of the original asphalt content. AE-150 was added by the cold process to restore the desired asphalt content. The reasons for employing this series are presented in Chapter 3.

Series #8 used the original mixtures prepared with the optimum asphalt content and oxidized to a penetration level of 30 by heating at 250 F (121 C) for 15 hours. Virgin aggregate and AE-150 were then added by the cold process, while the specimens for the others were fabricated through the cold process even when those specimens had no softening agent added. (Specimens 7-A, 7-D, 8-A and 8-D)

The initial test results including the Hveem Stabilometer Test are important from the standpoint of the mix design, while observation of the long-term trends in terms of the creep behavior was the main purpose of this study. This chapter, therefore, discusses the initial test results, and the long-term trends of the creep compliance and the creep parameters characterizing the viscoelastic properties of each series during the first half year after their fabrication. This chapter compares specimens chiefly within the series in a descriptive manner. Quantitative comparison of results between series is made in chapter 11.

In Table 16, concentration p , defined by Eq. (7-2) and the resulting asphalt consistencies of the blend are entered only for information. The consistency was calculated using the regression equations (7-4) and (7-5). In

the calculation for #7 series, the relationship given by Eqs. (7-6) and (7-7) were used to obtain the parameters in Eqs. (7-4) and (7-5). It must be noted that the accuracy in #7 series is not as good as in the other series.

8-2 #4 Series — Original Mixtures

8-2-1 Initial Properties

The initial physical properties of the six specimens in the #4 series involving the original mixtures are shown in Table 17. The stability S was observed with the specimens at 140 F (60 C), and the initial creep parameters were the values at 1 day of aging observed at room temperature. The stability S was computed from the defining equation given by Eq. (8-1):

$$S = \frac{22.2}{\frac{P_h D_2^2}{P_v - P_h} + 0.222} \quad (8-1)$$

where S = stabilometer value

D_2 = displacement on specimen

P_v = vertical pressure, 400 psi

P_h = horizontal pressure at the instant P_v is 400 psi

Some of the properties are plotted in Figure 16. In the figures, the observed values are connected by regressional functions with the second order polynomial form, using a computer subroutine.

TABLE 17 INITIAL PROPERTIES OF NO.4 SERIES - ORIGINAL MIXTURES

ITEM / SPECIMEN	4-1	4-2	4-3	4-4	4-5	4-6
ASPH. CONT.(PCT)	4.4	5.4	6.4	4.4	5.4	6.4
STABILITY S	42	44	37	41	43	36
HEIGHT (IN.)	2.57	2.57	2.51	2.60	2.57	2.54
SP. GR.	2.344	2.372	2.443	2.354	2.392	2.418
AIR VOIDS (PCT)	6.58	4.16	.04	6.18	3.31	.98
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	2.140E+04	2.086E+04	1.541E+04	2.203E+04	2.067E+04	1.619E+04
E2 (PSI)	3.595E+04	3.536E+04	2.603E+04	3.429E+04	3.604E+04	2.794E+04
ETA2 (PSI SEC)	1.184E+06	1.053E+06	7.130E+05	1.071E+06	1.025E+06	8.250E+05
ETA3 (PSI SEC)	1.113E+07	2.999E+07	1.623E+07	8.620E+06	1.497E+07	2.165E+07
TAU (SEC)	3.295E+01	2.979E+01	2.739E+01	3.122E+01	2.845E+01	2.952E+01
EH (PSI)	2.683E+04	2.624E+04	1.936E+04	2.682E+04	2.627E+04	2.050E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	5.410E-05	5.560E-05	7.650E-05	5.380E-05	5.680E-05	7.170E-05
60 SEC	7.510E-05	7.390E-05	1.016E-04	7.690E-05	7.630E-05	9.490E-05
300 SEC	1.012E-04	8.560E-05	1.211E-04	1.085E-04	9.570E-05	1.106E-04

FIGURE 16 INITIAL PROPERTIES
OF NO. 4 SERIES
-ORIGINAL MIXTURES

FIGURE 16 CONT.

The figures indicate the following:

- 1) The Hveem stability has the maximum value when the asphalt content is around the optimum value. The pattern of the curve is quite typical.
- 2) The percent air voids is about 4 percent at the optimum asphalt content. This confirms the validity of the mix design conducted in chapter 4.
- 3) The creep compliance values of the specimens with optimum asphalt content (5.4%) show the minimum values. Since the creep compliance $J(t)$ is proportional to the strain, this indicates that the mixture with the optimum asphalt content yields smaller strain than the mixtures with other asphalt contents.
- 4) All the parameters of the Burgers Model seem to be affected by the asphalt content. The moduli of elasticity, E_1 and E_2 , and their harmonic mean E_H , show a pattern similar to the Hveem Stability S . This might indicate that they are related to S in certain ways. Since the moduli of elasticity appear in the equation of creep compliance $J(t)$ in the reciprocal form, lower values of the moduli result in higher compliance, or higher strain on the basis of unit stress. As is found in Figures 16 (E) and (F), the moduli become smaller when the asphalt content exceeds the optimum value. This means that excessive asphalt content produces more deformable mixtures,

which is usually seen in practice. It must be noted that the change in moduli is larger in the plus side of the asphalt content than the minus side from the optimum content. This is to say that mixtures may be more deformable once the asphalt content exceeds its optimum value. Therefore an excessive asphalt content may be said to be more dangerous than the shortage of the content from the standpoint of inducing high strains.

- 5) The retardation time τ decreases as the asphalt content increases. Since smaller values of τ are indicated by the creep curve reaching the asymptotic line in shorter times as is indicated in Figure 9, the transitional regions of the mixtures with higher asphalt contents are shorter and the flow region (the region governed by η_3) dominates earlier.
- 6) Though scattering of data is seen in Figure 16 (H) for η_3 , the shape of the curve is significant. As is stated in chapter 6, η_3 is identical to the viscosity of mixture defined by Wood and Goetz (2). The figure indicates that η_3 varies with the asphalt content in the mixture. There seems to be a critical asphalt content that yields the maximum value of η_3 . This fact means that η_3 cannot be considered as a function of the consistency of asphalt cement alone, but also of other factors. Possible factors are the asphalt

content, the film thickness, percent air voids, aggregate gradation, aggregate surface texture, percentage of filler, etc. This fact may make it difficult to establish certain limits, especially the maximum limit, of the viscosity of mixture uniquely, though it was schematically described in Figure 1.

Observations 3), 4) and 7) may present another important point. They all indicate that a mixture yields minimum strain under the same stress level when the mixture contains the optimum asphalt content. This is supported by the observation that the moduli of elasticity E_1 , E_2 , and the viscosity η_3 show maximum values around the optimum asphalt content, and by the functional relationship given by Eq. (6-17). This phenomenon of smaller strain being produced due to mixture proportioning should be distinguished from a similar phenomenon caused by oxidation or weathering. The latter may be called hardening or oxidation hardening, while the former should be called stiffening instead of hardening.

8-2-2 Long-Term Properties — Creep Compliance

The creep behavior of the #4 series was observed every 7 days for one-half year. The compliance values at 10 sec., 60 sec., and 300 sec. for each specimen were plotted against age in days to note the general trend of the creep behavior.

Some of the curves are presented in Figures 17 (A) through 17 (C).

The following are observed from the figures:

- 1) At early ages the compliance generally decreases rapidly, and then the rate of decrease slows. Since the creep compliance is proportional to strain, this fact means that the specimens are becoming harder or stiffer with time. After 100 to 120 days of age, the creep compliance seems to increase again at a very slow rate.
- 2) It can commonly be observed in all of the figures that the three lines are almost parallel with each other. This might imply some parameters are almost constant with the age.
- 3) Curves for the specimens with OAC (optimum asphalt content) and OAC-1.0% can almost be superimposed, while the specimens with OAC+1.0% show values a little higher than the former. This indicates that the mixture with OAC+1.0% of asphalt is more easily deformed.
- 4) A big fluctuation in the curves for the #4-2 specimen is evident at around 160 days of age, which can not be seen with its counterpart (#4-4). The cause of the sudden rise is unknown.

4-1 (AP3=0AC-1.0)

FIGURE 17 CREEP COMPLIANCE CURVES
OF NO.4 SERIES - ORIGINAL MIXTURES

4-2 (AP3=0AC)

FIGURE 17 CONT.

4-3 (AP3=0AC+1.0)

FIGURE 17 CONT.

The fact observed in 1) above needs further discussion. As is cited in Chapter 2, Traxler and Schweyer (30) describe a phenomenon called time-hardening of asphalt cements. The hardening is said to increase very rapidly initially and to slow down as time passes. They expressed this phenomenon in the form given by

$$\eta = bt^m \quad (8-2)$$

where η is the absolute viscosity, t is time of aging in hours and b, m are constants.

A similar phenomenon was reported by Van der Burgh et al (75). They describe that a penetration value in their own aging process follows the equation for the first 7 days,

$$\text{Pen} = Ad^{-B} \quad (8-3)$$

where A and B are constants and d is the aging day. After the first 7 days, a penetration value is said to follow Eq. (8-4):

$$\text{Pen} = -Ed + F \quad (8-4)$$

where E and F are constants. Though they did not give a satisfactory physico-chemical explanation to the rate of aging, they conclude that all asphaltic bitumens and bituminous mixtures age in roughly the same way and according to the same rules, although there may be differences

in the rate of aging.

Though the curve fitting was not tried in this study, the discussion above appears to be applicable to the long-term creep behavior shown in Figure 17. That is, the long-term creep behavior may be said to represent the hardening effect of the bituminous mixtures fairly well. With respect to the slight increase after about 110 days of age, however, no good explanation is offered and further investigation may be called for.

8-2-3 Long-Term Properties — Creep Parameters

The parameters of the Burgers Model were computed on 18 representative observations. All values of B_1 , B_2 , B_3 , B_4 ; E_1 , E_2 , η_2 , η_3 , τ and E_H are listed in Appendix B and the average values of the six basic parameters E_1 , E_2 , η_2 , η_3 , τ and E_H are plotted in Figures 18 (A) through 18 (F). The average was taken between the two replicates of the same mix composition. In the figures, the specimens with OAC are plotted in solid lines, those with OAC-1.0% are in dotted lines, and the dashed lines indicate the specimens with OAC-1.0%. A quantitative comparison with other series is made in a later chapter, and only a descriptive comparison is made here as follows:

- 1) The first modulus of elasticity E_1 increases rather rapidly with time but suddenly decreases after 130 days of age. This sudden decrease may correspond to the increase of the compliance after 100 to 120 days.

FIGURE 18 CREEP PARAMETERS OF
NO.4 SERIES -ORIGINAL MIXTURES

FIGURE 18 CONT.

FIGURE 18 CONT.

FIGURE 18 CONT.

FIGURE 18 CONT.

FIGURE 18 CONT.

For the specimens with OAC+1.0% asphalt content, this phenomenon is not pronounced. The specimens with OAC and OAC-1.0% show almost the same trend.

- 2) The second modulus of elasticity E_2 shows a rather slow increase with time and no sudden decrease is found as was the case for E_1 . Again the specimens with OAC+1.0% show lower values than those with OAC and AOC-1.0%.
- 3) The curve for first viscosity η_2 shows almost the same pattern as E_2 .
- 4) Though differences are found in the second viscosity η_3 among the specimens for the first 20 days, the differences disappear after 20 days of age, and the values are almost the constant with time. Particular to this parameter is the fact that a decrease in the value is found on the second measurement. Though the figure does not show this clearly, the calculated values in Appendix B indicate that decreases are shown for specimens 4-2 and 4-6.
- 5) The retardation time τ increases very slowly with aging. Since τ is the ratio of η_2 to E_2 , this trend is expected from the results in 2) and 4). The specimens with OAC+1.0% asphalt content again show smaller values while the other two levels of asphalt content show almost the same values of τ .

- 6) The harmonic mean of the moduli of elasticity, E_H , shows a trend very similar to E_1 .

As is observed above, the specimens in the #4 series showed very slow increases in values of E_2 , η_2 , η_3 and τ , while E_1 and E_H showed a marked difference from the other parameters. If the observation made in Chapter 6 that E_H may be an indicator of aging can be assumed, the trend in E_H in this study indicates rather early weathering of the specimens, especially with the optimum and 1.0 percent less than optimum asphalt contents. However, this does not explain the sudden decrease after 100 to 120 days, and the latter phenomenon calls for another investigation. As was observed previously, the values of the creep compliance at 10 sec., 60 sec., and 300 sec. are almost parallel to each other and E_1 is the only parameter that appears to be related to the trend in the creep compliance curve. These observations may indicate that E_1 , which is related to the instantaneous response, is the dominant factor which governs the strain properties of specimens.

8-2-4 Summary

As a summary to this section, three points are raised:

- 1) Specimens generally show a rapid decrease in deformability with time initially, after which the rate of decrease becomes slow.

- 2) Changes in E_1 and E_H with time indicate rather early hardening of the specimens, but a sudden decrease in their values in 100 to 120 days cannot be explained simply by hardening due to oxidation. Other parameters show a slight increase in their values with aging.
- 3) Specimens at optimum asphalt content as determined by the Hveem Method tend to be stiffer and less deformable than those with other asphalt contents. This is true both initially and with aging. The use of excess asphalt results in more deformable mixtures, while an asphalt content slightly on the low side of optimum produces mixtures not greatly different from those with the optimum asphalt content.

8-3 #6 Series — AE-150 at Optimum Asphalt Content

8-3-1 Initial Properties

The original mixtures included in this series were made at optimum asphalt content. The mixtures were artificially weathered in the loose state to the level of a penetration of 30 in an oven with a temperature of 250 F (121 C) for 15 hours. After the process of artificial weathering, each mixture was loosened by vigorously stirring by hand with a spoon. Due to the highly viscous nature of the oxidized asphalt, large chunks could not be avoided entirely and the resultant gradation was not completely controlled. After several hours at room temperature,

the water and AE-150 were added. In the process of mixing, hand mixing was necessary in addition to using an electric mixer, otherwise large chunks segregated at the center. This may foretell a difficulty to be met in mixing in the field. After curing at 140 F for 1 hour, remixing was accomplished while the mixtures were hot. By doing this the large chunks seemingly disappeared. During the compaction, the specimens with 1.5 percent of AE-150 residue added showed a small amount of bleeding, and the amount of asphalt seemed to be a little too much. Generally speaking all of the mixtures were felt to be highly viscous compared with normal mixtures such as those in the #4 series.

The initial physical properties are shown in Table 18. The stability values S and R were measured after one day curing at room temperature. The stability S was computed according to the defining equation Eq. (8-1), but it must be kept in mind that the measurement was made at room temperature instead of 140 F (60 C) as in the standard procedure. The stability R was computed according to the formula given by Eq. (8-5):

$$R = 100 - \frac{100}{\frac{25}{d} \left(\frac{P_v}{P_h} - 1 \right) + 1} \quad (8-5)$$

TABLE 18 INITIAL PROPERTIES OF NO.6 SERIES
-AE-150 AT OPTIMUM ASPHALT CONTENT

ITEM / SPECIMEN	6-2	6-3	6-1	6-4	6-6	6-5
ASPH. CONT.(PCT)	5.4	5.4	5.4	5.4	5.4	5.4
AE-150(*) (PCT)	.5	1.0	1.5	.5	1.0	1.5
STABILITY S(**)	48	57	55	50	51	42
STABILITY R	93	93	93	94	93	91
HEIGHT (IN.)	2.74	2.76	2.76	2.75	2.76	2.76
SP. GR.	2.257	2.281	2.303	2.268	2.274	2.287
AIR VOIDS (PCT)	8.10	6.52	4.99	7.65	6.80	5.65
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	1.546E+04	1.613E+04	1.502E+04	1.933E+04	1.758E+04	1.260E+04
E2 (PSI)	3.202E+04	3.446E+04	3.171E+04	2.795E+04	3.289E+04	3.268E+04
ETA2 (PSI SEC)	9.180E+05	9.430E+05	8.630E+05	8.360E+05	8.750E+05	9.570E+05
ETA3 (PSI SEC)	2.446E+07	2.159E+07	1.973E+07	1.517E+07	2.182E+07	2.103E+07
TAU (SEC)	2.865E+01	2.735E+01	2.720E+01	2.990E+01	2.660E+01	2.929E+01
EH (PSI)	2.086E+04	2.197E+04	2.039E+04	2.285E+04	2.291E+04	1.819E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	7.340E-05	7.100E-05	7.620E-05	6.180E-05	8.800E-05	6.630E-05
60 SEC	9.340E-05	9.020E-05	9.720E-05	8.650E-05	1.087E-04	8.620E-05
300 SEC	1.073E-04	1.043E-04	1.129E-04	1.065E-04	1.239E-04	1.007E-04

(*) RESIDUE

(**) MEASURED AT
ROOM TEMPERATURE

where R = the stabilometer R-value

P_v = 160 psi vertical pressure

d = turns displacement reading

P_h = horizontal pressure when P_v is 160 psi.

Some of the initial properties are plotted in Figure

19. The following points are apparent:

- 1) The stability S data show wide scatter, but it seems that the maximum point exists at around 1.0% of AE-150 residue. Because this value was measured at room temperature, no comparison can be made with the standards.
- 2) The stability R decreases as the percentage of AE-150 residue increases. All of the values satisfy the minimum value of 78 for the emulsified asphalt aggregate base mixtures for heavy and very heavy traffic (76).
- 3) The percent air voids decrease with increases in the percentage of AE-150 residue. The values are rather high compared with the #4 series.
- 4) The creep compliance curves show small differences among the various percentage of AE-150 residue, though slightly higher values are seen for the specimens with 1.0% of AE-150 residue added.
- 5) The moduli of elasticity curves show patterns similar to those for the stabilities S and R , but the fluctuation in the moduli is rather wide.

FIGURE 19 INITIAL PROPERTIES
OF NO. 6 SERIES
- AE-150 AT OPTIMUM
ASPHALT CONTENT

FIGURE 19 CONT.

- 6) The viscosities η_2 and η_3 do not show differences among the specimens.
- 7) The curve representing retardation time τ shows an unusual shape. It has a minimum point at 1.0% of AE-150 residue.

The specimens in this series produced parameters that fluctuate over a wide range as compared with the specimens in #4 series. One of the causes may exist in the fluctuation in gradation after the artificial weathering. Though the artificially oxidized mixtures were loosened by stirring by hand, gradation control in loosened mixtures is difficult. When the gradation of the mixture is different, the surface area in the specimen becomes different, resulting in different film thicknesses around aggregate particles. This is believed to cause different properties in compacted specimens. Though the gradation control of pavement mixtures to be recycled is usually a very difficult task in the actual job also, the discussion above indicates the importance of gradation control in recycling projects.

The R value results seem to indicate that all of the mixtures would be satisfactory as the base course for heavy traffic roads. It is impossible, however, to determine the optimum asphalt content to be used in a job site from the results of the R values only. Other indices, such as the percent air voids, should be determined as

additional criteria. If the mixtures are to be used as surface or binder materials, some special processing may be required, because the mixtures here show a rather high percent of air voids. It is recommended that a minimum percent air voids of approximately 4 percent be provided for a surface course mixture (59), though the maximum value is not specified for the Hveem Method of mix design. To reduce air voids, application of higher compaction energy or a higher compaction temperature might be used. Adding more emulsion may be dangerous because bleeding was observed even at the level of 1.5 percent of AE-150 residue.

8-3-2 Long-Term Properties — Creep Compliance

The creep behavior of the #6 series was observed every 4 days for the first 20 observations and then approximately every 6 days for the remaining period up to one-half year. The compliance values at 10 sec., 60 sec., and 300 sec. for half of the specimens are plotted in Figures 20 (A), 20 (B), and 20 (C).

The following observations can be made:

- 1) At early ages, the curves for specimens with 0.5% of AE-150 residue added show almost the same shapes as are found in the #4 series. Specimens 6-3 and 6-5 with 1.0 and 1.5% AE-150 residue added show, however, a sudden increase on the second measurement, and decreasing trends thereafter.

FIGURE 20 CREEP COMPLIANCE CURVES
OF NO.6 SERIES - AE-150 AT OPTIMUM
ASPHALT CONTENT

6-3(AP3=0AC,AE150=1.0)

FIGURE 20 CONT.

6-5(AP3=0AC,AE150=1.5)

FIGURE 20 CONT.

- 2) As is the case with #4 series, curves for 10, 60 and 300 seconds are almost parallel with each other.
- 3) Curves for the specimens with 1.5 percent of AE-150 residue show much higher values than the others.
- 4) An observation with #4 series that the creep compliance increased again after 100 to 120 days of age is also seen with #6 series at about 70 days of age but the increasing rate is very small compared to the #4 series.

The observation that some of the specimens with higher contents of AE-150 residue showed an increase on the second observation is a very important fact in this study. Since an increase in the creep compliance means an increase in the strain, the observed fact indicates that higher deformation is taking place than would be expected with a virgin mixture such as one in the #4 series. This phenomenon may be called the softening effect, and this is discussed in chapter 11 in more detail.

Another sudden increase can be found with the sample 6-5 at 50 days of age, but the sudden change cannot be seen with other specimens. It is difficult to determine whether this increase has a special meaning in the physico-chemical change in the mixture or if it was caused for some other reason.

Since the creep compliance curves do not give any further information on the trend, this is discussed in more detail in the following section.

8-3-3 Long Term-Properties -- Creep Parameters

The parameters were computed on 19 representative observations, all the values are listed in Appendix B, and the average values of the six parameters are plotted in Figures 21 (A) through 21 (F). In the figures, the specimens with 0.5 percent of AE-150 residue are plotted in dotted lines, those with 1.0 percent are in solid lines, and those with 1.5 percent are in dashed lines. The following observations are made:

- 1) E_1 in this series shows a very similar magnitude and variation with age as that in #4 series. The time to reach a peak value is, however, much shorter and the magnitude of the peak values are smaller than in #4 series. This trend corresponds to the behavior of the creep compliance curves. Here again, the curves for the specimens with 0.5 percent and 1.0 percent of AE-150 residue are almost the same, while the curve for the specimens with 1.5 percent of AE-150 residue shows lower values. No decrease is observed for the first few days even though the creep compliance increases.

FIGURE 21 CREEP PARAMETERS OF NO.6 SERIES
-AE-150 AT OPTIMUM ASPHALT CONTENT

FIGURE 21 CONT.

FIGURE 21 CONT.

FIGURE 21 CONT.

FIGURE 21 CONT.

FIGURE 21 CONT.

- 2) E_2 also shows similar variation with age to that in #4 series, though in #6 series the specimens with 1.0 percent of AE-150 residue show higher E_2 values than the others. A sudden dip in the curve is observed for the first few days, and the magnitude of the dip seems to be proportional to the amount of AE-150 residue added.
- 3) η_2 shows similar variation with age to that in #4 series. However, the specimens with 1.0 percent of AE-150 residue present higher values than the others again. An initial dip in the curve is observed only with the specimens with 1.5 percent of AE-150 residue. η_2 also shows very similar trends to E_2 . This suggests the constancy of τ , since τ is the ratio of η_2 to E_2 .
- 4) The magnitudes and general shapes of the curves for η_3 are similar to those for #4 specimens, but two points are different. First, the initial sudden decrease for the #6 series is conspicuous, and the magnitude of the decrease is seemingly proportional to the levels of AE-150 residue added. Secondly the specimens with 1.0 percent of AE-150 residue added show the highest values after 2 weeks of age.
- 5) The retardation time τ does not vary appreciably among the specimens.

As is also seen in the observation of the creep compliance curves, the observations above now clearly indicate the softening effect taking place inside some of the specimens. The decrease in η_3 at early ages is seen with some specimens with higher asphalt content in #4 series, and the trend is more pronounced in the #6 series. This fact indicates that excessive asphalt may cause a decrease in η_3 even when the asphalt is the original asphalt. This effect is clearly seen in η_3 and, if the magnitude is large, it is found in E_2 and η_2 , but never in E_1 .

With respect to long-term behaviors, the specimens with 1.0 percent of AE-150 residue added show higher values in all the parameters except for τ which shows small differences. Though higher values in E_1 , E_2 , η_2 or η_3 may not always be desirable, the fact is that the specimens with 1.0 percent of AE-150 residue are stiffer than the others. If moderate stiffness is taken as the index of an optimum mixture, the specimens with 1.0 percent of AE-150 residue may be the optimum mixture among the mixtures in #6 series. It should be noted that in the discussion of the initial properties for the #6 series, the optimum asphalt content was difficult to determine and Figure 19 did not necessarily indicate that 1.0 percent of AE-150 residue is optimum. This may indicate that recycled mixtures may require a longer time of observation than normal mixtures to determine the optimum mixture.

8-3-4 Summary

The following statements can be made in summary of this section:

- 1) With respect to long-term behavior, the specimens in #6 series showed similar creep behavior to those in #4 series.
- 2) A softening effect was found on the second observation. This is clearly seen in the trend of η_3 and is also indicated in the values of η_2 and E_2 .
- 3) Though the Hveem Design data did not determine the optimum asphalt content of AE-150 residue, the long-term behavior indicates that the specimens with 1.0 percent of AE-150 residue are stiffer than the others, and if stiffness can be the index of the optimum mixture, the content of 1.0 percent of AE-150 may be taken as the optimum. This mixture may be used as a base course mixture, if the Hveem criteria are to be followed.

8-4 #7 Series — AE-150 at Reduced Asphalt Content

8-4-1 Initial Properties

This series of tests utilized the original mixtures with the asphalt content reduced by certain amounts before being oxidized at 140 F (60 C) for 15 hours. This oxidation yielded a penetration of about 60 for the extracted asphalt as is shown in Table 9. Various amounts of AE-150 residue

were added by cold process to bring the total asphalt content to three predetermined values.

This series consists of three sub-series, 7 A-F, 7G-L, and 7M-R. The 7A-F sub-series consists of the original mixtures with the optimum asphalt content, the 7G-L sub-series has the original mixtures with 1.0 percent less than the optimum asphalt content, and the 7M-R sub-series has the original mixtures with 2.0 percent less than the optimum asphalt content. The amount of AE-150 residue were determined so that the total asphalt content becomes 5.4, 5.9 and 6.4 percent by the weight of aggregate.

The idea for this series of tests is based on the assumption as is described in chapter 3 that some part of the old asphalt cement may work as an inert portion like aggregate, which could be removed without affecting the effective portion of the asphalt. If the conceptual model presented in chapter 1 is followed, the outer sphere of the asphalt film around an aggregate particle may be considered to have been oxidized heavily, but the inner part may well be considered still to be less viscous. The basic idea assumes the very hard outer sphere to be inert. Thus if the inert outer layer could be removed, the remaining part might consist of less viscous asphalt cement.

A question might be raised as to the nominal consistency level of asphalt inside specimens in 7G-L and 7M-R sub-series which were subjected to oxidation at reduced

asphalt contents. The nominal consistency level here refers to that consistency of asphalt inside a compacted specimen oxidized at reduced asphalt content which produces the same creep behavior as a specimen oxidized at optimum asphalt content. For example, if a specimen with 0.5 percent less than optimum asphalt content is subjected to oxidation to a penetration level of 60 and yields the same creep behavior as another specimen with the optimum asphalt content and subjected to oxidation of a penetration 25 level, the nominal consistency of the former is said to be 25. The former is acting as if it contained optimum asphalt with a penetration level of 25. Since the specimens of sub-series 7A-F were oxidized at optimum asphalt content, the nominal consistency is equal to the real consistency and it is a penetration level of about 60. To determine the nominal consistency for sub-series 7G-L and 7M-R may be very difficult, however. The only possible way to estimate it would be to utilize the relationship between the log of penetration and E_H as is described in Chapter 6. The sub-series 7G-L has the same asphalt content and oxidation condition as specimens 4-1 and 4-4. Thus the regression equation Eq. (6-30) could be used with the value of E_H from Table 17, and the estimated penetration is 28. Therefore the 7G-L sub-series may be said to have a nominal penetration of 28. The specimens of sub-series 7M-R do not have any counterpart in another series, and

it is impossible even to estimate the nominal consistency. It must be borne in mind, however, that there is no proven evidence in this estimation procedure. This fact suggests that the concept of reducing asphalt content previously before oxidation could be acceptable conceptually, but it is very difficult to apply in practice.

Though one of the main purposes of this series was to find the validity of the concept discussed above, another aspect has an important meaning as well. As is shown in Table 16, the 7A-F sub-series has the original mixture with the optimum asphalt content, and it was oxidized to the penetration level of about 60. When this sub-series is compared with the #6 series, the 7A-F sub-series has another meaning if a less oxidized mixture is to be recycled. Therefore, an investigation may be made as to whether there is any difference in properties of recycled mixtures between the highly oxidized and less oxidized original mixtures.

Some observations were made in the process of specimen fabrication. After oxidation at 140 F for 15 hours, the mixtures in this #7 series seemed to be less viscous than in the #6 series. Though the problem of formation of large chunks was still present to a slight extent, stirring vigorously by hand was easier. After adding AE-150, re-mixing by hand was also necessary. After curing in the oven at 140 F (60 C) for 1 hour, mixtures with higher

amounts of AE-150 such as 7-H, 7-I, 7-K, 7-L and the 7M-R sub-series, seemed to be wet and tender. Among them 7-O and 7-R specimens were clearly wetter than others, and stuck to the foot of the compactor even though the foot was heated to about 140 F (60 C). Bleeding was taking place in those specimens naturally.

The initial physical properties are presented in Table 19. The note made in 8-3-1 on the stability values R and S is still applicable in this section. Some of the initial values are plotted in Figure 22. In Figure 22 the dependent variables are plotted against the percentage of AE-150 (residue added to the total mixture).

In order to understand the effects of some factors, the analysis of variance (ANOVA) (77) was made in two ways; the first is a two-way ANOVA with the factors being the initial asphalt content A and the total asphalt content, T. The second ANOVA is a one-way ANOVA with the factor being the amount of AE-150 residue added to the original Mixture, X. The models are as follows:

$$Y_{ijn} = A_i + T_j + AT_{ij} + \epsilon_{(ij)n} \quad (8-6)$$

$$Y_{kn} = X_k + \epsilon_{(k)n} \quad (8-7)$$

$$i = 1, 2, 3 \quad j = 1, 2, 3 \quad k = 1, 2, \dots, 9 \quad n = 1, 2$$

where Y_{ijn} = coded value of dependent variables, the Hveem Stabilities S and R, specific gravity, percent air voids, E_1 , E_2 , η_2 , η_3 , τ and E_H , of the n^{th} replicant for the i^{th} initial asphalt content and the j^{th} total asphalt content.

TABLE 19 INITIAL PROPERTIES OF NO.7 SERIES
-AE-150 AT REDUCED ASPHALT CONTENT

(A) SPECIMENS 7A-F

ITEM / SPECIMEN	7-A	7-B	7-C	7-D	7-E	7-F
ASPH. CONT. (PCT)	5.4	5.4	5.4	5.4	5.4	5.4
AE-150(*) (PCT)	0.0	.5	1.0	0.0	.5	1.0
STABILITY S(**)	55	39	36	60	51	36
STABILITY R	92	91	88	92	92	89
HEIGHT (IN.)	2.44	2.32	2.30	2.34	2.36	2.34
SP. GR.	2.321	2.390	2.403	2.378	2.376	2.402
AIR VOIDS (PCT)	6.22	2.77	1.56	3.92	3.34	1.60
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	1.628E+04	1.336E+04	1.224E+04	1.412E+04	1.336E+04	9.580E+03
E2 (PSI)	3.095E+04	1.691E+04	1.965E+04	2.569E+04	1.899E+04	1.321E+04
ETA2 (PSI SEC)	7.650E+05	4.380E+05	4.340E+05	6.000E+05	5.070E+05	2.710E+05
ETA3 (PSI SEC)	2.865E+07	1.646E+07	1.987E+07	2.493E+07	1.568E+07	1.418E+07
TAU (SEC)	2.472E+01	2.590E+01	2.208E+01	2.317E+01	2.669E+01	2.052E+01
EH (PSI)	2.133E+04	1.493E+04	1.508E+04	1.828E+04	1.569E+04	1.111E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	7.210E-05	9.350E-05	1.000E-04	8.420E-05	9.110E-05	1.333E-04
60 SEC	9.260E-05	1.310E-04	1.317E-04	1.085E-04	1.254E-04	1.795E-04
300 SEC	1.037E-04	1.513E-04	1.470E-04	1.209E-04	1.458E-04	2.000E-04

(*) RESIDUE
(**) MEASURED AT
ROOM TEMPERATURE

TABLE 19 CONT.

(B) SPECIMENS 7G-L

ITEM / SPECIMEN	7-G	7-H	7-I	7-J	7-K	7-L
ASPH. CONT.(PCT)	4.4	4.4	4.4	4.4	4.4	4.4
AE-150(*) (PCT)	1.0	1.5	2.0	1.0	1.5	2.0
STABILITY S(**)	44	37	41	36	38	26
STABILITY R	92	88	91	89	89	85
HEIGHT (IN.)	2.34	2.36	2.36	2.36	2.32	2.33
SP. GR.	2.383	2.388	2.397	2.365	2.407	2.418
AIR VOIDS (PCT)	3.68	2.81	1.76	4.41	2.04	.90
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	1.320E+04	1.327E+04	9.720E+03	1.350E+04	1.119E+04	8.540E+03
E2 (PSI)	2.982E+04	3.085E+04	2.145E+04	4.207E+04	2.511E+04	1.836E+04
ETA2 (PSI SEC)	7.090E+05	6.810E+05	4.420E+05	9.500E+05	5.350E+05	3.920E+05
ETA3 (PSI SEC)	2.275E+07	3.701E+07	1.911E+07	3.088E+07	2.178E+07	1.307E+07
TAU (SEC)	2.376E+01	2.209E+01	2.060E+01	2.258E+01	2.133E+01	2.134E+01
EH (PSI)	1.830E+04	1.856E+04	1.338E+04	2.044E+04	1.548E+04	1.166E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	8.720E-05	8.690E-05	1.208E-04	8.260E-05	1.043E-04	1.373E-04
60 SEC	1.094E-04	1.064E-04	1.497E-04	9.750E-05	1.289E-04	1.712E-04
300 SEC	1.222E-04	1.148E-04	1.648E-04	1.064E-04	1.422E-04	1.936E-04

(*) RESIDUE

(**) MEASURED AT

ROOM TEMPERATURE

TABLE 19 CONT.

(C) SPECIMENS 7M-R

ITEM / SPECIMEN	7-M	7-N	7-O	7-P	7-Q	7-R
ASPH. CONT.(PCT)	3.4	3.4	3.4	3.4	3.4	3.4
AE-150(*) (PCT)	2.0	2.5	3.0	2.0	2.5	3.0
STABILITY S(**)	60	40	17	38	33	24
STABILITY R	94	89	75	89	88	84
HEIGHT (IN.)	2.34	2.36	2.30	2.34	2.33	2.33
SP. GR.	2.376	2.386	2.435	2.391	2.403	2.417
AIR VOIDS (PCT)	3.92	2.85	.20	3.32	2.16	.94
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	1.144E+04	8.640E+03	9.070E+03	1.030E+04	1.104E+04	7.090E+03
E2 (PSI)	4.760E+04	3.436E+04	4.207E+04	3.765E+04	4.869E+04	2.850E+04
ETA2 (PSI SEC)	9.400E+05	6.940E+05	8.880E+05	8.330E+05	1.169E+06	5.570E+05
ETA3 (PSI SEC)	4.026E+07	3.221E+07	2.575E+07	3.509E+07	4.440E+07	2.006E+07
TAU (SEC)	1.975E+01	2.020E+01	2.111E+01	2.211E+01	2.400E+01	1.955E+01
EH (PSI)	1.844E+04	1.380E+04	1.493E+04	1.617E+04	1.799E+04	1.136E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	9.570E-05	1.271E-04	1.191E-04	1.064E-04	9.740E-05	1.549E-04
60 SEC	1.090E-04	1.449E-04	1.343E-04	1.226E-04	1.103E-04	1.764E-04
300 SEC	1.158E-04	1.534E-04	1.452E-04	1.316E-04	1.176E-04	1.906E-04

(*) RESIDUE

(**) MEASURED AT
ROOM TEMPERATURE

FIGURE 22 INITIAL PROPERTIES
OF NO. 7 SERIES
-AE-150 AT REDUCED ASPHALT CONTENT

FIGURE 22 CONT.

FIGURE 22 CONT.

FIGURE 22 CONT.

y_{kn} = coded value of the dependent variables of the n^{th} replicant for the i^{th} initial asphalt content and the j^{th} total asphalt content.

A_i = effect of the i^{th} initial asphalt content (fixed)

T_j = effect of the j^{th} total asphalt content (fixed)

AT_{ij} = effect of the interaction of A_i and T_j .

X_k = effect of the k^{th} amount of AE-150 (fixed)

$\epsilon_{(ij)n}$ = within error, normally and independently distributed with zero mean and variance σ^2 .

Because the specimens were prepared in a sub-series, the design is a randomized complete block design, and there should be a restriction error in such a way that it completely confounds with A_i . However in the analysis the blocking factor was eliminated from the model since all of the specimens were fabricated in a homogeneous and equal condition and the restriction error was assumed to be negligible. The calculation of ANOVA was made by means of the SPSS sub-program ANOVA (78) in the Purdue University Computing Center. The results are shown in Table 20, where the double asterisks indicate the factor is significant at the 1 percent level and the single asterisk denotes that the factor is significant at the 5 percent level.

Using Tables 19 and 20 and Figure 22, the following observations are made with respect to the initial properties:

- 1) The Hveem Stability S decreases as the total asphalt content increases.

Table 20 ANOVA for #7 Series

Dependent Variable	Two-Way ANOVA			One-Way ANOVA
	A	T	Interaction AT	
Stability S	-	**	-	-
Stability R	-	*	-	*
Specific Gravity	-	*	-	-
Percent Air Voids	-	**	-	-
Creep Parameters				
E_1	**	**	-	*
E_2	**	*	-	-
τ	*	*	-	*
η_2	*	*	-	-
η_3	**	*	-	-
E_H	-	**	-	-

Note: A: the initial asphalt content
T: the total asphalt content
X: the amount of AE-150 residue

- 2) The Hveem Stability R shows a similar trend to S . One observation shows a very low value of 75, which is lower than the criterion for the heavy and very heavy traffic base mixture (76).
- 3) The percent air voids decreases as the total asphalt content increases.
- 4) The moduli of elasticity E_1 and E_2 decrease as the total asphalt content increases, but the level of original asphalt content affects E_1 and E_2 differently. This difference is conspicuous when Figure 22 (F) for E_2 and Figure 22 (E) are compared. The figures indicate that the smaller the original asphalt content the larger E_2 becomes, while E_1 decreases under the same conditions.
- 5) The same pattern as is in E_2 is seen with viscosities η_2 and η_3 .
- 6) The retardation time τ is almost constant though a small decrease can be seen as the amount of AE-150 added increases.
- 7) Since E_1 and E_2 show the opposite pattern, their harmonic mean E_H is only significant with the level of the total asphalt content.
- 8) The creep compliance values indicate that in general the specimens with higher amounts of AE-150 residue have higher compliance values. This means that the greater the amount of AE-150 residue contained in the mixture, the softer the mixture becomes in general.

The observations 5) and 6) have an important meaning in using AE-150 as a softening agent. It is not the amount of AE-150 residue (X) alone that affects the increasing trends in E_2 , η_2 and η_3 , because, if such were the case, the lines in Figures 22 (F), (G), (H) should be continuous. It is observed that the total asphalt content also affects those values. In general, as the total asphalt content becomes less and the amount of AE-150 residue increases, higher values E_2 , η_2 and η_3 are obtained. This indicates that there is a certain optimum total asphalt content which will produce maximum value of E_2 , η_2 or η_3 in each sub-series.

From the viewpoint of mix design, it would be possible to determine the optimum amount of AE-150 residue to add to the oxidized mixtures. Since the stability R is satisfied by all the average values of each proportion, all the mixtures could be used as the base course material. When the percent air voids is taken into account, however, all the specimens show rather small values. If the minimum percent air voids is set at 4 percent, the 7A-F sub-series results show 0.25 percent as the optimum amount of AE-150 residue, and the 7G-L and the 7M-R sub-series results show 1 percent and 2.0 percent of AE-150 residue respectively. The latter means that the optimum total asphalt content does not change after recycling in the 7G-L and the 7M-R sub-series.

Comparison of the mixtures for the 7A-F sub-series with #6 series shows interesting results. It is true that the problem of formation of chunks after oxidation was observed with the #7 series as was the case with the #6 series, but the specific gravity and the percent air voids for the 7A-F sub-series are much better than the #6 series mixtures and similar to the original mixture before oxidation even though the 7A-F sub-series was fabricated by the cold process. This suggests that the highly oxidized mixtures of the #6 series are more difficult to handle, or to mix with AE-150 and to compact than the less oxidized mixtures of the #7 series. It appears that the mixtures of the 7A-F sub-series might possibly be used as surface mixtures as well as base course mixtures. Of course a more thorough investigation should be conducted before concluding that they can be used as surface mixtures, however.

8-4-2 Long-Term Properties — Creep Compliance

The creep behavior of specimens in the #7 series was observed every 4 days for the first 10 times of observation and then approximately every 6 days for the remaining period up to one-half year. The compliance values of some specimens are plotted in Figure 23.

The following is observed:

- 1) The initial values of creep compliance are very high in all of the specimens as compared with the values at

7-D(AP3=0AC,AE150=0.0)

FIGURE 23 CREEP COMPLIANCE CURVES OF NO. 7 SERIES
- AE-150 AT REDUCED ASPHALT CONTENT

7-E(AP3=0AC,AE150=0.5)

FIGURE 23 CONT.

7-F(AP3=0AC,AE150=1.0)

FIGURE 23 CONT.

7-J(AP3=0AC-1.0,AE150=1.0)

FIGURE 23 CONT.

7-K(AP3=0AC-1.0,AE150=1.5)

FIGURE 23 CONT.

7-L(AP3=0AC-1.0,AE150=2.0)

FIGURE 23 CONT.

7-M(AP3=0AC-2.0,AE150=2.0)

FIGURE 23 CONT.

7-N(AP3=0AC-2.0,AE150=2.5)

FIGURE 23 CONT.

7-0(AP3=0AC-2.0,AE150=3.0)

FIGURE 23 CONT.

later ages, and the magnitude is larger the higher the amount of AE-150 residue contained in the specimens.

- 2) A sharp decrease in the creep compliance value is generally found after a few days with the specimens with high amounts of AE-150 residue especially such specimens as 7-F, 7-L, 7-I, 7-O and 7-R.
- 3) Within a sub-series, the specimens with a higher content of AE-150 residue show higher compliance values in general, but between the sub-series, this is not always true. The specimens 7-C and 7-F show the highest values throughout all ages.
- 4) Some specimens show a small increase in the compliance on the second measurement. This phenomenon is found in 7-A, 7-D, 7-F, and 7-J. Since the first two samples contain no AE-150, this phenomenon cannot always be said to be caused by the softening effect of the softening agent.
- 5) As was found in the #4 and #6 series, the three lines in each figure are almost parallel with each other, but the differences between the lines seem to be narrower in the 7G-L and 7M-R sub-series than in the 7A-F sub-series.

Observations 1) and 2) above are important. Since the specimens of the 7G-L sub-series have a nominal consistency of 28 penetration, they could be compared to those of the #6 series. When the two series are compared, it is clear

that there are many differences and they cannot be said to be identical to each other. As mentioned in 1) and 2), the 7G-L sub-series has higher initial values and sharper decreases during the early ages. The 7G-L specimens show softer properties than the #6 specimens in general. This fact means that the concept of considering a highly oxidized portion as being inert is not necessarily true. The highly oxidized portion might be inert chemically, but its existence may be important to the physical properties of the mixtures. Additionally even a highly oxidized portion might be dispersed by a softening agent in the long-run, though no clear evidence was found in the time frame of those studies.

Comparison of the 7A-F sub-series with the #6 series yields another important result. As is generally indicated in 1) and 2), the specimens of the 7A-F sub-series have high initial values and a steep decrease in creep compliance values with time and they are larger than in the #6 series. This fact may indicate that the effect of the liquid character of the emulsion explicitly appears initially in the 7A-F sub-series, but that the softening reaction takes place more rapidly than in the harder mixtures. The liquid character of the emulsion results in easier handling of the mixtures when the asphalt cement is less viscous. That is, the mixtures with less viscous asphalt cement after oxidation can be more easily loosened than ones with harder

asphalt and the resultant gradation of the recycled mixture may be finer resulting in good lubrication by the emulsion. The highly viscous mixtures may have a coarser gradation and stronger interlocking between chunks resulting in less lubrication effect of the emulsion. In summary, a mixture with less age and containing a less viscous asphalt may be more easily recycled with only a small percentage of an appropriate emulsified asphalt than a highly oxidized mixture with a highly viscous binder.

The observation 4) is a perplexing observation. The same phenomenon of an increase in the creep compliance on the second measurement was found to be a systematic trend in the #6 series of tests, but the results here are irregular and not systematic. As it was found in the #4 series that the viscosity of the mixture η_3 sometimes increases on the second measurement even though AE-150 residue is not present in the mixture, this phenomenon might also be caused by something other than the softening agents alone. This suggests the desirability for more research on this point.

8-4-3 Long-Term Properties — Creep Parameters

The creep parameters were computed on 19 representative observations. All the values are listed in Appendix B and the average values of the six parameters are plotted in Figures 24 (A) through 24 (R). The figures are plotted for each sub-series. In the figures, the specimens with 5.4%

FIGURE 24 CREEP PARAMETERS OF NO.7 SERIES
-AE-150 AT REDUCED ASPHALT CONTENT

GRAPH OF E2

SERIES=7AF,AP3(0AC)+AE150

(B)

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

FIGURE 24 CONT.

total asphalt content are plotted in dotted lines, those with 5.9% total asphalt content are in solid lines and those with 6.4% total asphalt content are in dashed lines. A quantitative analysis of these results is made in Chapter 11 including a comparison with other series. Only a descriptive comparison is made here as follows:

- 1) Curves for E_1 values present very similar trends to #4 and #6 series specimens in general, i.e., increase at early ages and a small decrease afterwards. The peak of E_1 seems to appear at about 50 days of age, which is earlier than in the #4 and #6 series. A significant increase as is found in the #4 series at 80 and 100 days of age cannot be seen in this series, but an almost constant trend is found after the early increase. All the specimens show that the greater the total asphalt content becomes, the smaller E_1 becomes or the softer the mixture.
- 2) A significant point with E_2 is that a moderate increase is found in the 7A-F sub-series, while an almost constant trend after a steep increase for a short period is seen in the 7M-R sub-series. Another point attracting attention is that the values of E_2 decrease as the level of total asphalt content (the factor T in Eq. (8-6)) increases in the 7A-F sub-series, while in the 7G-L sub-series E_2 stays at almost the same level with increase asphalt content. In the 7M-R

sub-series, E_2 increases as T increases. Since a different level of the original asphalt content (the factor A in Eq. (8-6)) is given to each sub-series, this fact suggests that the interaction of T and A affects the behavior of E_2 in the long-term behavior.

- 3) The trend in η_2 is very similar to that in E_2 , which may suggest that their ratio τ is almost constant.
- 4) A very significant point with η_3 is that, as the amount of AE-150 residue increases, the value of η_3 seems to increase and the differences are very large among the specimens with different amounts of AE-150 residue. Secondly the trend in η_3 is unstable for the first 2 or 3 weeks, especially in the 7A-F sub-series. It was seen in #4 and #6 series that as the total asphalt content increases, the values of η_3 decrease in general. In the 7A-F sub-series, however, no clear differences are seen, the 7G-L and 7M-R sub-series show the inverse; the more the asphalt content, the larger η_3 becomes though the initial values are smaller. This fact implies that AE-150 is effective in raising η_3 and that concentration of the agent may influence the level of η_3 . Thirdly, a drop in the value of η_3 is also found with some specimens after 5 to 10 days of age, not always on the second observation. Therefore the softening effect is considered to take place even though this phenomenon cannot be

clearly noticed from the creep compliance curves.

- 5) As is pointed out in 3), the retardation time τ shows an almost constant trend, though the 7A-F sub-series shows a very small increase throughout all the observation period. A significant point is that the greater the concentration of AE-150 residue, the smaller the value of τ becomes.
- 6) E_H does not seem to be affected strongly by some factors. Especially, the magnitudes of E_H in the 7G-L and 7M-R sub-series are almost at the same level.

The observations above indicate in summary that AE-150 tends to increase the value of η_3 after 2 or 3 weeks of an unstable period and to decrease the retardation time τ . A small value of τ means that the transitional region is small and the flow region is approached earlier as is seen in Figure 9. A large value of η_3 means that the slope of the flow portion of the curve is small. The two facts mean, when they are combined, that the strain response to a sudden application of stress is rapid and strain level does not increase much after the application. That is, the mixture is becoming more solid-like and less like a viscous material. Then the high-float type of emulsion may be said to produce a stiffer mixture than AP-3 does. Furthermore, a large value of η_3 contributes to decreasing the permanent deformation as depicted by Eq. (6-25).

This result suggests, therefore, that AE-150 produces a favorable mixture from the standpoint of prevention of rutting caused by the permanent deformation due to traffic loads.

8-4-4 Summary

The results presented in this section may be summarized as follows:

- 1) Reducing the asphalt content of the original mixture before oxidation to simulate very highly weathered mixtures may be described conceptually, but evaluation of the resulting mixture in a practical meaning is very difficult because the consistency level of the simulated mixture, or the nominal consistency level is difficult to estimate. Furthermore, even if the highly oxidized portion is considered to be inert chemically, its existence affects the physical properties of the mixture. Then application of this concept to the long-term observation of recycled mixtures may be difficult in a practical sense.
- 2) Slightly weathered mixtures may be recycled easily by adding a small percentage of an emulsion, while greatly weathered mixtures may be difficult to mix with an emulsion and compact in the field. From the standpoint of mix design, the latter may be used only as base course mixtures at most, while the former have the possibility to be used as binder, or even surface

mixtures provided other conditions such as skid resistance, resistance to abrasion etc. are satisfied. This also implies that a conventional mix design may be used to design slightly weathered recycling mixtures, while it may not be sufficient if design for greatly weathered mixtures is required.

- 3) A high-float type of emulsion AE-150 is found to decrease the retardation time and to increase the viscosity of the mixture. This fact implies that the resulting mixture has a non-viscous property and has small permanent deformation.

8-5 #8 Series -- AE-150 Mixtures with Added Aggregate

8-5-1 Initial Properties

In recycling old pavement mixtures, some amount of virgin aggregate with a softening agent is frequently required. The purpose in this section is to investigate the behavior of such mixtures. In this study, 3 levels of virgin aggregate were added and 3 levels of the amount of AE-150 (residue) were used so as to make the total asphalt content 5.4 (original optimum value), 5.9 and 6.4 percent.

The original mixtures used in this series contained the optimum amount of asphalt. The mixtures were artificially weathered to the level of a penetration of 30 by heating in an oven at a temperature of 250 F (121 C) for 15 hours in the loose condition. Since each specimen was fabricated separately from the beginning of mixture preparation, the

exposure area in the pan was adjusted when it was subjected to the heat, e.g., the mixture to which 25 percent of virgin aggregate (25 percent of the total weight of aggregate) was to be added occupied 75 percent of the area of the 11 in. X 7 in. pan and the remaining area was kept vacant. This was done in order to equate the surface area directly exposed to the air flow in the oven. After the weathering, each mixture was cooled to room temperature, during which each was loosened with a spoon. The problem of large chunks still existed. After about four hours at room temperature, 1 percent of water was added to the weathered mixture and virgin aggregate separately and the two were then mixed by hand. After 10 minutes, the full amount of AE-150 was added to the virgin aggregate and mixed for 30 seconds to 1 minute with an electric mixer to obtain a good coating. Immediately after mixing, it was mixed with the weathered mixture for 2 minutes with the mixer. At this time it was commonly observed with all mixtures that AE-150 once covering the virgin aggregate was displaced and the aggregate pieces became uncoated. In order to check if this phenomenon would take place with a different procedure, the old mixture and the virgin aggregate were first mixed, 1 percent of water added, cured for 10 minutes and then AE-150 was added. Coating of the larger pieces was not improved by this procedure and so it was not used. After mixing, the mixture was placed in

the oven at 140 F (60 C) for 1 hour and remixed. By remixing with the mixer for 2 minutes, the coating was somewhat improved, but still the coating was not uniform. The samples without any agent, i.e., samples 8-A and 8-D, lacked cohesion and were difficult to handle and compact as was the case with the samples in #6 series. Some of the other specimens showed bleeding during compaction, especially with larger amounts of AE-150. After this step, the procedure used was the same as is described in Chapter 5.

The results of the Hveem Stabilometer Test and the related analyses are shown in Table 21 and in Figure 25. In the figures, the dependent variables are plotted against the percentage of AE-150 (residue) added to the total mixture.

In order to understand the effects of some factors, the ANOVA was made in two ways; the first is a two-way ANOVA with the factors being the amount of the virgin aggregate X_1 , and the total asphalt content X_2 . The second ANOVA is a one-way ANOVA with the factor of the amount of AE-150 residue added to the original mixture, X_3 . Though the procedure was deemed to be homogeneous throughout the preparation of mixtures, a factorial block design (77) was used in the experiment in this series. The reason for employing this design method was purely mathematical.

TABLE 21 INITIAL PROPERTIES OF NO.8 SERIES
-AE-150 MIXTURES WITH ADDED AGGREGATE

(A) SPECIMENS 8A-F

ITEM / SPECIMEN	8-A	8-B	8-C	8-D	8-E	8-F
TOTAL AS CONT.(PCT)	5.4	5.9	6.4	5.4	5.9	6.4
VIRGIN AGG.(PCT)	0.0	0.0	0.0	0.0	0.0	0.0
STABILITY S(*)	63	55	58	67	57	67
STABILITY R	94	94	94	94	94	94
HEIGHT (IN.)	2.50	2.45	2.45	2.47	2.50	2.43
SP. GR.	2.255	2.291	2.321	2.291	2.273	2.311
AIR Voids (PCT)	8.89	6.79	4.92	7.43	7.53	5.33
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	2.072E+04	2.000E+04	1.746E+04	2.048E+04	2.058E+04	1.733E+04
E2 (PSI)	3.102E+04	3.165E+04	2.252E+04	3.224E+04	2.627E+04	2.441E+04
ETA2 (PSI SEC)	1.133E+06	1.052E+06	7.800E+05	1.149E+06	8.710E+05	8.300E+05
ETA3 (PSI SEC)	1.579E+07	1.872E+07	1.223E+07	1.417E+07	1.029E+07	1.296E+07
TAU (SEC)	3.654E+01	3.326E+01	3.463E+01	3.564E+01	3.315E+01	3.400E+01
EH (PSI)	2.484E+04	2.451E+04	1.967E+04	2.505E+04	2.308E+04	2.027E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	5.600E-05	5.800E-05	6.860E-05	5.640E-05	5.880E-05	6.790E-05
60 SEC	7.780E-05	7.880E-05	9.840E-05	7.790E-05	8.560E-05	9.550E-05
300 SEC	9.900E-05	9.710E-05	1.257E-04	1.002E-04	1.156E-04	1.210E-04

(*) MEASURED AT
ROOM TEMPERATURE

TABLE 21 CONT.

(B) SPECIMENS 8G-L

ITEM / SPECIMEN	8-G	8-H	8-I	8-J	8-K	8-L
TOTL AS CONT.(PCT)	5.4	5.9	6.4	5.4	5.9	6.4
VIRGIN AGG.(PCT)	25.0	25.0	25.0	25.0	25.0	25.0
STABILITY S(*)	52	43	50	58	61	47
STABILITY R	93	91	91	92	93	91
HEIGHT (IN.)	2.44	2.44	2.40	2.38	2.38	2.40
SP. GR.	2.267	2.316	2.345	2.335	2.323	2.350
AIR VOIDS (PCT)	8.33	5.74	3.89	5.58	5.45	3.69
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	1.513E+04	1.303E+04	1.501E+04	1.552E+04	1.408E+04	1.257E+04
E2 (PSI)	3.275E+04	2.721E+04	2.723E+04	2.437E+04	2.399E+04	1.701E+04
ETA2 (PSI SEC)	9.680E+05	7.710E+05	7.320E+05	7.270E+05	6.890E+05	4.930E+05
ETA3 (PSI SEC)	2.330E+07	1.783E+07	1.689E+07	1.213E+07	1.685E+07	6.680E+06
TAU (SEC)	2.955E+01	2.834E+01	2.687E+01	2.983E+01	2.872E+01	2.895E+01
EH (PSI)	2.070E+04	1.762E+04	1.935E+04	1.897E+04	1.774E+04	1.446E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	7.460E-05	8.770E-05	7.800E-05	7.610E-05	8.320E-05	9.710E-05
60 SEC	9.430E-05	1.119E-04	1.025E-04	1.042E-04	1.105E-04	1.396E-04
300 SEC	1.094E-04	1.295E-04	1.205E-04	1.294E-04	1.298E-04	1.821E-04

(*) MEASURED AT
ROOM TEMPERATURE

TABLE 21 CONT.

(C) SPECIMENS 8M-R

ITEM / SPECIMEN	8-M	8-N	8-O	8-P	8-Q	8-R
TOTL AS CONT.(PCT)	5.4	5.9	6.4	5.4	5.9	6.4
VIRGIN AGG.(PCT)	50.0	50.0	50.0	50.0	50.0	50.0
STABILITY S(*)	53	48	49	44	48	42
STABILITY R	92	91	91	89	90	89
HEIGHT (IN.)	2.42	2.39	2.41	2.38	2.40	2.39
SP. GR.	2.334	2.354	2.368	2.349	2.360	2.377
AIR VOIDS (PCT)	5.58	4.11	2.91	4.98	3.87	2.54
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	1.262E+04	1.231E+04	1.150E+04	1.256E+04	1.113E+04	1.047E+04
E2 (PSI)	3.320E+04	3.138E+04	4.390E+04	3.367E+04	4.047E+04	2.937E+04
ETA2 (PSI SEC)	7.560E+05	7.530E+05	1.107E+06	7.530E+05	1.018E+06	8.070E+05
ETA3 (PSI SEC)	2.091E+07	2.222E+07	3.244E+07	1.902E+07	2.479E+07	1.284E+07
TAU (SEC)	2.277E+01	2.432E+01	2.523E+01	2.236E+01	2.516E+01	2.746E+01
EH (PSI)	1.829E+04	1.768E+04	1.822E+04	1.829E+04	1.746E+04	1.544E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	9.010E-05	9.160E-05	9.420E-05	9.030E-05	9.790E-05	1.059E-04
60 SEC	1.103E-04	1.126E-04	1.087E-04	1.101E-04	1.297E-04	0.
300 SEC	1.231E-04	1.259E-04	1.187E-04	1.244E-04	1.258E-04	1.523E-04

(*) MEASURED AT
ROOM TEMPERATURE

FIGURE 25 INITIAL PROPERTIES
OF NO. 8 SERIES
-AE-150 MIXTURES
WITH ADDED AGGREGATE

FIGURE 25 CONT.

FIGURE 25 CONT.

FIGURE 25 CONT.

The two factors X_1 and X_2 had three levels, respectively, and duplicate specimens were made. Since 6 specimens could be fabricated in a day with the day being a block, a factorial block design of 3 blocks of 6 each was used. As the confounding piece with the blocks, an interaction term $X_1 X_2$ was used. Solving the defining equation

$$X_1 + X_2 = 0, 1, 2 \quad (\text{mod } 3) \quad (8-8)$$

the 3 blocks are given in Table 22. The ANOVA for this block design is shown in Table 23.

The model for the one-way ANOVA is given by:

$$Y_{kn} = Y_{3k} + \epsilon_{(k)n} \quad (8-9)$$

$$k = 1, 2, \dots, 9, \quad n = 1, 2$$

where Y_{kn} = coded value of the dependent variables of the n^{th} replicant for the k^{th} amount of AE-150 residue

X_{3k} = effect of the k^{th} amount of AE-150 residue (fixed)

$\epsilon_{(k)n}$ = within error

The calculation of ANOVA was made by means of the SPSS sub-program ANOVA, and the results are shown in Table 24.

Using Tables 21 and 24 and Figure 25, the following are found with respect to the initial properties of mixtures in the #8 series — those with virgin aggregate added:

Table 22 Treatment Combinations in Blocks of # 8 Series

Block	Solution			Treatments			Specimen Identification
	X_1	X_2	X_4	X_1 (%)	X_2 (%)	X_4 (%)	
B1	0	0	0	0	5.4	1	8-A
	0	0	1	0	5.4	2	8-D
	1	2	0	25	6.4	1	8-I
	1	2	1	25	6.4	2	8-L
	2	1	0	50	5.9	1	8-N
	2	1	1	50	5.9	2	8-Q
B2	0	1	0	0	5.9	1	8-B
	0	1	1	0	5.9	2	8-E
	1	0	0	25	5.4	1	8-G
	1	0	1	25	5.4	2	8-J
	2	2	0	50	6.4	1	8-O
	2	2	1	50	6.4	2	8-R
	0	2	0	0	6.4	1	8-C
	0	2	1	0	6.4	2	8-F
	2	0	0	25	5.9	1	8-H
	2	0	1	25	5.9	2	8-K
	1	1	0	50	5.4	1	8-M
	1	1	1	50	5.4	2	8-P

Note: X_1 : the factor of the amount of the virgin aggregate with 3 levels (fixed)

X_2 : the factor of the total asphalt content with 3 levels (fixed)

X_4 : replication with 2 levels (random)

Table 23 ANOVA for Block Design of #8 Series

Source	d.f.	
Blocks and/or $X_1 X_2$	2	
Restriction Error	0	
X_1	2	
X_2	2	
X_4	1	
$X_1 X_2$ (actually $X_1 X_2^2$)	2	} Pooled to Test
$X_2 X_4$	2	
$X_1 X_4$	2	
$X_1 X_2 X_4$ $X_1 X_2^2 X_4$	4	
Error	0	
Total	17	

Table 24 ANOVA for #8 Series

Dependent Variable	Two-Way ANOVA			One-Way ANOVA
	X_1	X_2	Interaction $X_1 X_2$	
Stability S	**	-	-	-
Stability R	**	-	-	**
Specific Gravity	**	*	-	**
Percent Air Voids	**	**	-	**
Creep Parameters				
E_1	**	**	-	**
E_2	*	-	-	-
τ	**	*	**	**
η_2	*	-	-	-
η_3	-	-	-	-
E_H	**	*	-	**

Note: X_1 : the amount of the virgin aggregate

X_2 : the total asphalt content

X_3 : the amount of AE-150

* 5 percent level significance

** 1 percent level significance

- 1) Hveem Stabilities S and R show significant changes as the amount of virgin aggregate is changed. In general, as the amount of virgin aggregate increases, the stability values decrease. Since the increase in the amount of virgin aggregate is directly related to the increase in the amount of AE-150 residue and the total asphalt content does not increase, this fact seems to indicate an initial softening effect of AE-150. With respect to the criterion, all the specimens satisfy the Hveem stability R for a base course material.
- 2) Both the amount of the virgin aggregate and the total asphalt content affect the air voids and the specific gravity. The air voids decrease and the specific gravity values increase as the levels of the two factors increase. This type of phenomenon is usually seen in mixture design when asphalt content is increased. That is, the asphalt functions as if it were a lubricant. The 8A-F sub-series specimens, which contain no virgin aggregate and can be compared to those of the #6 series, show air void values slightly on the high side, but those in the other sub-series show a favorable range.
- 3) The modulus of elasticity E_1 values show similar trends as the values for stability S or R, while the E_2 values are very different in the 8M-R sub-series.

This sub-series shows higher values for E_2 than the other sub-series, which also was observed in #7 series for specimens without virgin aggregate added.

- 4) The viscosity η_2 values also show a very different pattern which is similar to that found with E_2 .
- 5) The retardation time τ is affected by all the factors. In general, as the virgin aggregate increases, and as the amount of AE-150 residue increases, the retardation time decreases.
- 6) Although Figure 25 (H), for variation in the viscosity η_3 , shows a similar pattern as is shown for η_2 or E_2 , the viscosity η_3 fluctuates over very wide range and no definite conclusion can be made.

The observations in 3) and 4) are the same as were discussed in the last section for the series where no virgin aggregate was added. It may be concluded, therefore, that as more AE-150 residue is added to the original mixture, increases in E_2 and η_2 , and possibly η_3 may be expected.

From the standpoint of mixture design, the optimum amount of AE-150 residue would be determined. The mixtures of the 8A-F sub-series may be used as base course materials with around 1.0 percent of AE-150 (residue) as the optimum content. The mixtures of the 8G-L and 8M-R sub-series might be used even as surface of binder mixtures from the standpoint of air voids and stability provided other factors are satisfied. In this case the optimum amounts of

AE-150 (residue) are around 2 and 3 percent respectively. This discussion may indicate that even highly weathered mixtures could be satisfactorily recycled when the proper amount of virgin aggregate and the emulsion are added. But as was found in the preparation procedure for these mixtures, stripping of asphalt film from the virgin aggregate should be investigated in more detail.

8-5-2 Long-Term Properties — Creep Compliance

The creep behavior of the #8 series specimens was observed every 4 days for the first 10 times of observation and then approximately every 6 days for the remaining period up to one-half year. The compliance values are plotted in Figures 26 (A) through 26 (I).

The following observation are made:

- 1) In the 8A-F sub-series, to which no virgin aggregate was added, the specimens with the highest total asphalt content show higher compliance values than the others at early ages, but the difference seems to disappear in about 50 days. The remaining specimens, with the asphalt contents of 5.4 percent and 5.9 percent, show almost the same magnitude from the initial observation.
- 2) In the 8G-L sub-series with 25 percent of virgin aggregate added, the same trend found in 1) is observed. The initial compliance value for the specimen 8-L is

8-A(AP3=0AC,AE150=0.0, AGG=0)

FIGURE 26 CREEP COMPLIANCE CURVES OF NO.8 SERIES
-AE-150 MIXTURES WITH ADDED AGGREGATE

FIGURE 26 CONT.

8-C(AP3=0AC,AE150=1.0, AGG=0)

FIGURE 26 CONT.

FIGURE 26 CONT.

8-I (AP3=0AC, AE150=2.35, AGG=25)

FIGURE 26 CONT.

8-J(AP3=0AC,AE150=1.35,AGG=25)

FIGURE 26 CONT.

8-P(AP3=0AC,AE150=2.68,AGG=50)

FIGURE 26 CONT.

8-Q(AP3=0AC,AE150=3.18,AGG=50)

FIGURE 26 CONT.

8-R(AP3=0AC,AE150=3.68,AGG=50)

FIGURE 26 CONT.

significantly higher than for any other specimens, but its magnitude reduces to the level of the others in about a month.

- 3) In the 8M-R sub-series with 50 percent of virgin aggregate, the differences in compliance values between specimens with different amounts of asphalt are small.
- 4) An initial decrease in compliance value is seen with all the specimens except for the specimen 8-H. The rate of decrease is more rapid in the 8A-F sub-series than the others. The 8M-R sub-series specimens show very slow decreases in compliance value with age.
- 5) The specimen 8-H is the only specimen which shows an increase in compliance on the second observation.

The observations in 1), 2) and 4) indicate that as the amount of AE-150 increases, the longer it will take for a specimen to reach a stable condition. That is, a longer length of curing period may be required for mixtures with higher contents of an emulsion.

As is observed above, all the specimens seem to approach a certain level of compliance value at the end of the observation period, and significant differences among them can hardly be seen. As far as this fact is concerned, any of the mixtures might be considered for possible use, because only the same level of strain will be induced by

the traffic load, but detailed observation may suggest that there are some important differences among them. These are difficult to find from the creep compliance data only and further investigation by means of the viscoelastic model follows in the next section.

8-5-3 Long-Term Properties — Creep Parameters

The creep parameters were computed on 17 representative observations. All the values are listed in Appendix B and the average values of the six parameters are plotted in Figures 27 (A) through 27 (R). The figures show plots for each sub-series. In the figures, the specimens with 5.4 percent of total asphalt are plotted in dotted lines, those with 5.9 percent of the total asphalt are in solid lines, and those with 6.4 percent of total asphalt are in dashed lines. Descriptive comparison follows:

- 1) The plots of E_1 represents an increasing trend at early ages and then continues to be almost constant instead of decreasing afterwards as was seen in the #6 series. Curves for the 8A-F sub-series show rather steep increase in E_1 at early ages and a little more variation than the others. This trend disappears as the order of the sub-series proceeds; i.e., the increase at early ages become less steep and less variation is found. In the 8M-R sub-series differences among specimens with the three levels of total asphalt content are very small.

FIGURE 27 CREEP PARAMETERS OF NO.8 SERIES
-AE-150 MIXTURES WITH ADDED AGGREGATE

FIGURE 27 CONT.

FIGURE 27 CONT.

FIGURE 27 CONT.

FIGURE 27 CONT.

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FIGURE 27 CONT.

FIGURE 27 CONT.

FIGURE 27 CONT.

- 2) The values of E_2 show a sharp increase at early ages but almost constant in 40 to 60 days. As the amount of virgin aggregate increases, the differences among the curves for different levels of total asphalt content become very small.
- 3) With respect to η_2 , the 8A-F sub-series results show higher values than the other two-series. Differences between curves for the two different levels of virgin aggregate and different levels of total asphalt content are hardly detectable.
- 4) A conspicuous fact with η_3 is that as the order of the sub-series increases (increasing amounts of virgin aggregate and AE-150 residue), the magnitude of η_3 increases significantly. The early rate of increase is high but an almost constant level is reached after 40 to 60 days. An initial drop in η_3 is found in specimens 8-G, 8-H, and 8-O, but not systematically.
- 5) The retardation time appears to be almost constant throughout the observation period. A significant fact is that the retardation time becomes smaller as the sub-series proceed from 8A-F to 8M-R, i.e., the amount of virgin aggregate and AE-150 residue increase.
- 6) E_H shows basically the same trend as E_1 and E_2 . The magnitude becomes smaller as the order of sub-series proceeds from 8A-F to 8M-R.

Since the order of the sub-series is identical to the increase in the virgin aggregate and new asphalt, the above observation that some parameters are affected by the order of the sub-series means that they are affected by the new asphalt and/or the virgin aggregate. Therefore it is proper to note that η_3 increases and τ decreases as the percentage of AE-150 residue increases.

The softening phenomenon was not found systematically in this series. The 8A-F series has the same conditions as the #6 series and the latter showed the softening phenomenon on the second observation to a great extent. The reason why the softening phenomenon is not apparent in the #8 series is not clear.

8-5-4 Summary

As a summary to this section, the following statements are made:

- 1) As would be expected, the recycled mixtures with virgin aggregate and emulsified asphalt tend to exhibit more of the properties of the newly added materials as their content increases.
- 2) From the viewpoint of mix design, a heavily weathered mixture may be recycled satisfactorily when virgin aggregated and an emulsified asphalt are added.

- 3) In the process of mixing an old mixture with virgin materials, removal of the film of emulsion may take place with new aggregate. This phenomenon needs further investigation.

CHAPTER 9

TEST RESULTS — OTHER SOFTENING AGENTS

9-1 Scope

The last chapter described the test series in which mixtures were tested with and without the addition of emulsified asphalt AE-150. This chapter presents the results of experiments of the four series with agents other than AE-150. The agents used here were emulsified Mobilsol, Reclamite, AE-300 and AC-2.5. The basic information for tests with these agents is presented in Table 25. It was decided to use the artificially weathered mixtures with the optimum asphalt content (5.4 percent) and without any virgin aggregate, because use of this mixture provides a basis for comparing the properties with other mixtures presented in Chapter 8. The original mixture was weathered to the level of penetration 30 in an oven at 250 F (121 C) for 15 hours, as described in Chapter 4.

In determining the content for the addition of the two rejuvenating agents, Mobilsol and Reclamite, the consistency of the blend of the agent and the old asphalt cement in the old mixture was set at 1000 poises absolute viscosity. Any level of consistency could be employed in the use of the rejuvenating agents, but in this study, it

Table 25 Basic Information for Mixtures Using Other Softening Agents

Softening Agent	Specimen Notation	Original Mixture	Agent in Percent by Agg. Weight (%)	Total Bitumen Content (%)	Concentration p (%)	Calculated Blend Consistency	
						Viscosity (poise)	Pen (dmm)
Mobilsol	M-1, M-2	Oxidation: 250 F, 15 hr Asphalt Content: OAC* (5.4%)	0.6	6.0	12.3	1000	92
Reclamite	R-1, R-2		0.6	6.0	11.5	1000	92
AE-300	E-1, E-3		0.5	5.9	8.5	2514	39
	E-2, E-4		1.0	6.4	15.6	1296	48
AC-2.5	C-1, C-3		0.5	5.9	8.5	5166	33
	C-2, C-4		1.0	6.4	15.6	3977	41

* Optimum Asphalt Concent

was decided to restore the old asphalt cement to its original consistency which happens to be about 1000 poises. The concentration p to yield 1000 poises in the blend was determined by means of the blending curve given in Figure 15. The concentration was determined in this way and the penetration value was estimated from the blending curve of Figure 15 (B) for information. The total bitumen content and the percentage of the agent by aggregate weight in Table 25 are calculated values from the concentration p .

The series with Mobilsol has two specimens, designated as the M series. The series with Reclamite has two specimens and is named as the R series. The two series were fabricated on different days.

The specimens with AE-300 are called the E series. The amount of AE-300 added was established to increase the asphalt content in the mixture by 0.5 percent increments, following conventional mix design procedures rather than using blending curves. The blend consistency in Table 25 is calculated by means of the regression equations given in Chapter 6 for information only.

The specimens with AC-2.5 are named the C series. The level of the asphalt content and the blend consistency were determined in the same way as in the E series.

The initial tests in these series are almost the same as those presented in Chapter 8, and the results are shown in the following sections in the same way. It must be

noted that the Hveem Stability S was measured at the same time as the stability R at room temperature for all of the specimens discussed in this chapter.

In the series with the two rejuvenating agents and AE-300, the specific gravity was not measured according to ASTM D2726, Standard Test Method for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens, because these agents are soft and may be oily rather than asphaltic and it was feared that they might be washed away when the specimens were submerged into the water. Instead, the percent air voids was estimated by the following formula:

$$\left. \begin{aligned} V &= 0.43 + 0.785X \\ X &= \left(\frac{D_{\max} - \frac{W}{SH}}{D_{\max}} \right) \times 100 (\%) \end{aligned} \right\} \quad (9-1)$$

where V is the estimated air voids in percent, $D_{\max}$ is the theoretical maximum density, W, S, and H are the weight, the surface area of the flat end, and the height of each specimen respectively. The formula was obtained through a regression analysis with the data from the specimens discussed in Chapter 8. The coefficient of correlation was 0.973 and the number of specimens used was 48. Therefore the formula may be considered to give a fairly good estimate as long as the same original mixtures are used in estimation.

9-2 Rejuvenating Agents — Mobilsol and Reclamite

9-2-1 Initial Properties

Since the two agents, Mobilsol and Reclamite were in the emulsified form, the specimens were fabricated in the same fashion as described in Chapter 5 for the emulsified asphalt. The two agents mixed very well with the weathered mixtures with one percent of water added and the coating seemed to be perfect. Because Mobilsol is yellow and Reclamite is pink in color, the miscibility was easily detected by observing the change of colours around aggregate particles. After being subjected to heat at 140 F (60 C) for 1 hour, the mixtures were workable enough to compact as easily as if they were original mixtures at 230 F (110 C).

The initial physical properties are shown in Table 26. Some of the results are plotted in Figure 28. As a basis of comparison, the corresponding values of specimens 8-A and 8-D are also plotted. The two specimens had the original mixtures oxidized to a penetration 30 and compacted without any softening agent. Since the specimens with the rejuvenating agents have a total content of 6.0 percent, it would be logical to compare them with the specimens with that amount of asphalt. There are no specimens having AP-3 with the content of 6.0 percent, however, so that the specimens 8-B and 8-E, with 5.4

TABLE 26 INITIAL PROPERTIES OF M AND R SERIES -MOBILSOL AND RECLAMITE

ITEM / SPECIMEN	M-1	M-2	R-1	R-2	8-A	8-D	8-B	8-E
ASPH. CONT.(PCT)	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
AGENT (*) (PCT)	.6	.6	.6	.6	0.0	0.0	.5	.5
STABILITY S(**)	51	52	61	47	63	67	55	57
STABILITY R	91	92	93	92	94	94	94	94
HEIGHT (IN.)	2.47	2.47	2.49	2.51	2.50	2.47	2.45	2.50
AIR VOIDS (PCT)	6.62	6.31	7.23	6.94	8.89	7.43	6.79	7.53
CREEP PARAMETERS (5 MIN. LOADING)								
E1 (PSI)	1.878E+04	1.877E+04	1.618E+04	1.344E+04	2.072E+04	2.048E+04	2.000E+04	2.058E+04
E2 (PSI)	3.295E+04	3.269E+04	2.989E+04	2.927E+04	3.102E+04	3.224E+04	3.165E+04	2.627E+04
ETA2 (PSI SEC)	8.750E+05	9.090E+05	7.840E+05	7.460E+05	1.133E+06	1.149E+06	1.052E+06	8.710E+05
ETA3 (PSI SEC)	1.972E+07	2.065E+07	1.480E+07	1.257E+07	1.579E+07	1.417E+07	1.872E+07	1.029E+07
TAU (SEC)	2.657E+01	2.782E+01	2.622E+01	2.548E+01	3.654E+01	3.564E+01	3.326E+01	3.315E+01
EH (PSI)	2.392E+04	2.385E+04	2.100E+04	1.842E+04	2.484E+04	2.505E+04	2.451E+04	2.308E+04
CREEP COMPLIANCE (1/PSI)								
10 SEC	6.280E-05	6.230E-05	7.270E-05	8.570E-05	5.600E-05	5.640E-05	5.800E-05	5.880E-05
60 SEC	8.340E-05	8.260E-05	9.560E-05	1.056E-04	7.700E-05	7.790E-05	7.880E-05	8.560E-05
300 SEC	9.840E-05	9.800E-05	1.149E-04	1.315E-04	9.900E-05	1.002E-04	9.710E-05	1.156E-04

(*) RESIDUE

(**) MEASURED AT
ROOM TEMPERATURE

FIGURE 28 INITIAL PROPERTIES
OF M AND R SERIES
-MOBILSOL AND RECLAMITE

FIGURE 28 CONT.

percent of AP-3 and 0.5 percent of AE-150, were chosen, and their values are also plotted as a reference in the figure.

The following observations are made:

- 1) The specimens with the rejuvenating agents show values of Hveem Stability R and S that are smaller than the original mixtures. However, they still remain at satisfactorily high values.
- 2) The creep compliance $J(t)$ seems to be higher for specimens with Reclamite than for the others.
- 3) The specimens with Reclamite show the smallest values of E_1 , η_2 , η_3 , τ and E_H .
- 4) Mobilsol shows higher values of η_3 than the others.
- 5) The retardation time τ is at the same level in the specimens with the two agents and is lower than for specimens with original asphalt only.
- 6) The estimated percent air voids of the specimens with Reclamite and Mobilsol are at the level of 7 percent which is lower than for specimens without rejuvenating agents added.

As is indicated in 2) and 3) above, Reclamite seems to yield softer mixtures than Mobilsol as indicated by initial property values. From this observation it is estimated that Reclamite may have a higher rate of reaction than Mobilsol. This difference is interesting in comparing the two rejuvenating agents, because they seem to have

almost the same composition as shown in Chapter 4, and because they are supposed to yield the same blend consistency of 1000 poises.

Item 4) of the observed results indicating that the specimens with Mobilsol have higher values of η_3 may mention that Mobilsol has a tendency to raise η_3 at least at early ages. This may be expected from the observation in Chapter 7 that Mobilsol showed a thixotropic character while Reclamite did not.

The two points of discussion above suggest that Reclamite and Mobilsol may have different characteristics even though reported chemical analyses show their compositions to be almost the same (25).

With respect to mixture design, the specimens with Reclamite and Mobilsol satisfy the requirement in the Hveem Stability R for a base course material. As far as their appearance is observed, they might be used as a surface course material. However, the percent air voids is estimated to be rather high for a surface course mixture. In order to check the air void content obtained by the estimation technique, two trial samples with Mobilsol were fabricated and the percent air voids was obtained. Their values were about 7 percent, which means the estimate technique may be appropriate. Therefore the specimens with Mobilsol and Reclamite with the target consistency at 1000 poises can be said not to be suitable as a surface material

as they currently exist and some modification should be made to the mixtures. This fact indicates that the design procedure used in this study for rejuvenating agents using blending curves only may not be satisfactory.

9-2-2 Long-Term Properties — Creep Compliance

The creep behavior of M and R series specimens using Mobilsol and Reclamite was observed every 2 days for the first 15 times of observation, and every 4 days for the next 5 times, and then every 6 days for the remaining period up to about 100 days. The compliance values are plotted in Figures 29 (A) and 29 (B).

The following are observed from the figures:

- 1) The Reclamite series shows higher initial values in creep compliance as indicated in observation 2) of the previous section, but on the second observation dropped to a very low level. Mobilsol series shows a rather milder decrease than Reclamite.
- 2) Both the Mobilsol and Reclamite series show a small increase in compliance values at about 2 weeks after fabrication.
- 3) The Mobilsol series show higher creep compliance values than those for Reclamite in general up to 50 days, after which the two series seem to yield almost the same level of compliance values and the compliance values afterwards slowly increase.

M-1 (MØBILSØL)

FIGURE 29 CREEP COMPLIANCE CURVES
OF M AND R SERIES -MØBILSØL AND RECLAMITE

FIGURE 29 CONT.

- 4) Mobilsol specimens show a sudden increase in values of creep compliance at 50 days of age.

Observation 1) is important, because this indicates that Reclamite causes hardening or stiffening much earlier than Mobilsol does. In the last section Reclamite was found to react with the weathered mixture initially to a higher degree than Mobilsol. Reclamite can then be said to react with weathered asphalt rapidly with reaction ceasing in a short period, while Mobilsol reacts in a milder way.

The increase in creep compliance values in two weeks is seen with both agents. The reason for this increase is not clear, but it might be explained by assuming that delayed reaction between the agent and the old asphalt cement is taking place. The next large increase found with the M series in 50 days after fabrication might be caused by the same delayed reaction, but a satisfactory explanation is difficult. As a whole, trends in values of creep compliance for specimens with Mobilsol can be said to be variable up to about 50 days and the trends with Reclamite up to about 30 days.

The phenomenon of a slow increase in creep compliance after 50 days of age has been observed also in #4 series and the reason for this increase of softening trend cannot be explained with the data so far obtained.

9-2-3 Long-Term Properties — Creep Parameters

The creep parameters were computed on 22 representative observations. All of the values are listed in Appendix B and the average values of the six parameters are plotted in Figures 30 (A) through 30 (F). In the figures, the M series is plotted in a dotted broken line and the R series is in a solid line.

The following observations are noted from the comparison:

- 1) The specimens with Reclamite added showed significant increases in a first few days in all parameters except for τ .
- 2) With respect to E_1 , E_2 and E_H the M series generally shows smaller values than the R series after the second observation. This indicates that the instantaneous response to load on the specimen is greater with the M series than the R series. Especially, the M series shows smaller values in E_2 up to about 80 days of age. In general, the two agents present almost constant values in E's, though a very slight increase is seen in E_2 of the Mobilsol series and a decrease in all E's of the Reclamite series.
- 3) Regarding τ , the M series shows smaller values than the R series throughout the observation period except for the very first observation. The two series show almost constant and much lower levels in τ than the

FIGURE 30 CREEP PARAMETERS OF M AND R SERIES
-MOBILSOL AND RECLAMITE

FIGURE 30 CONT.

FIGURE 30 CONT.

FIGURE 30 CONT.

FIGURE 30 CONT.

FIGURE 30 CONT.

8A-F sub-series and as low as the 8G-L sub-series.

- 4) There is a big difference in the level of η_2 between the two agents. The M series show lower values than the R series, and the former has an almost similar trend to the 8M-R and the latter to the 8A-F sub-series.
- 5) A significant difference in the level of η_3 can be seen in the two series. In the R series, Reclamite increased the value of η_3 some 2.5 times during the first four days and after which it was almost constant for 50 days before decreasing to a lower level. The M series also shows a rapid increase in η_3 during the first few days, but the level is comparatively low and the trend is almost constant. The levels of η_3 in the two agents is higher than the 8A-F and 8G-L sub-series and as high as in the 8M-R sub-series.

Some of the observations above indicate that Reclamite reacts with the weathered asphalt in the specimens very rapidly, compared to Mobilsol and other agents. Especially the rapid increase is seen in η_3 and E_2 .

The high level of η_3 in the R and M series suggest that they present a thixotropic nature. The M series has been found to have the thixotropic nature from the very beginning of the observation. The R series did not, but it seems to appear in a few days after mixing with the old asphalt.

The phenomenon of η_3 decreasing in several weeks in the Reclamite series cannot be seen in any other series except the E series to be discussed in the next section. The cause of this phenomenon is not clear. One possible reason may be that the thixotropic nature disappears through a long-term reaction. It was observed that the R and M series show an increase in the creep compliance after 60 days of age. The decreasing trend of η_3 in the R series might be corresponding to the slow increase in the compliance. A closer observation of the creep compliance curve of the R series indicates that the spaces between the lines for $t=300$ sec. and for $t=60$ sec., and between the lines for $t=60$ sec. and $t=10$ sec., increase as the age increases after about 60 days. Because the spaces between the two lines are related to the inverse of η_3 , the observation of a decrease in η_3 can be said to be expected from the creep behavior. This cannot be seen with the M series. In #4 and #6 specimens the increase in the compliance values was related chiefly to the decrease in E_1 , but this is not the case with the R series. If this trend of decreasing η_3 should continue for the rest of the life of the mixture in the R series, the high level of η_3 might be said to be a temporary phenomenon and the small permanent deformation caused by high value of η_3 could not be expected. Further observation for this series is required.

The decreasing trend in η_3 in the R series may indicate another point. The general decrease in the creep compliance as the age passes has been regarded as "hardening". But it is now made clear that hardening is not always related to the aging or oxidation in asphalt cement alone, but it might also be explained by the thixotropic character in asphalts such as AE type emulsions or the rejuvenating agents such as Mobilsol or Reclamite. Anderson et al (25) describe that a stiffening of the mixes due to the laboratory aging was observed and generally related to the measured hardening of the binders. However, they continue that the Reclamite mix stiffened more than the other mixes containing softening agents though the binder in the Reclamite mix measured by extraction hardened less than the other agents. This phenomenon with Reclamite may be considered to be caused by the thixotropic property. Since the binder in the mixture did not show a high level of oxidation, the phenomenon of decrease in the creep compliance may preferably be called stiffening rather than hardening, though it may be sometimes difficult to distinguish the two phenomena.

9-2-4 Summary

In this section the initial and the long-term creep behavior of the recycled specimens with Mobilsol or Reclamite added were discussed. The following observation

may be pointed out as a summary:

- 1) Reclamite seems to react with the old asphalt cement much more rapidly than Mobilsol does. Initially, Reclamite causes softening, but in a few days the mixture stiffens more than Mobilsol. Mobilsol reacts at a moderate rate with the old asphalt cement.
- 2) Both agents present a certain character, which causes a high level of η_3 , but the character in Reclamite seems to disappear after about two months, while it does not disappear in the case of Mobilsol. Further observation of the specimens may be required.
- 3) From the standpoint of mix design, the two agents as used rejuvenated the mixtures to a condition satisfactory as base course materials. Due to the high percentage of air voids, the rejuvenated mixtures cannot be used as a surface course as they are, and some changes are required.

9-3 Softening Agent AE-300

9-3-1 Initial Properties

Since AE-300 is an emulsion of the same kind as AE-150 but containing a softer residue, the procedure of fabrication of the specimens was completely the same as was employed to fabricate the specimens with AE-150. The base asphalt of AE-300 is the AC-2.5 which was used in this study and is to be discussed in the next section.

Probably because the base asphalt of AE-300 has a lower viscosity than that of AE-150, the mixtures with AE-300 were easier to handle after heating at 140 F (60 C) for 1 hour. In the process of compaction, the specimens with 1.0 percent of AE-300 added showed a light degree of bleeding.

The initial properties are shown in Table 27. Some of the properties are plotted in Figure 31. This series can be compared with the 8A-F sub-series, the only difference being the use of AE-300 instead of AE-150. To provide a basis of comparison, the values for specimens 8-A and 8-D which contain zero percent AE-300 residue are also plotted in the figure.

To know the differences caused by different grades of AE type emulsion, a two-way ANOVA was made. The model for the ANOVA is given by

$$Y_{ijk} = A_i + B_j + AB_{ij} + \epsilon_{(ij)k} \quad (9-1)$$

$$i = 1, 2 \quad j = 1, 2, \quad k = 1, 2$$

where Y_{ijk} = coded value of the dependent variables of the k^{th} replicant with i^{th} type of AE emulsion and j^{th} level of asphalt content.

A_i = the effect of the i^{th} type of AE emulsion.
 $i = 1$ for AE-150 and $i = 2$ for AE-300.

B_j = the effect of the j^{th} level of asphalt content. $j = 1$ for 0.5 percent of added emulsion residue or 5.9 percent of total asphalt content and $j = 2$ for 1.0 percent of added emulsion residue or 6.4 percent of total asphalt content.

TABLE 27 INITIAL PROPERTIES OF E SERIES -AE-300

ITEM / SPECIMEN	E-1	E-2	E-3	E-4	8-A	8-D
ASPH. CONT.(PCT)	5.4	5.4	5.4	5.4	5.4	5.4
AE-300 (*) (PCT)	.5	1.0	.5	1.0	0.0	0.0
STABILITY S(**)	51	55	54	54	63	67
STABILITY R	93	92	93	92	94	94
HEIGHT (IN.)	2.51	2.51	2.46	2.47	2.50	2.47
AIR VOIDS (PCT)	8.09	6.32	6.82	5.74	8.89	7.43
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	2.031E+04	1.534E+04	2.233E+04	1.813E+04	2.072E+04	2.048E+04
E2 (PSI)	3.575E+04	3.431E+04	3.414E+04	3.261E+04	3.102E+04	3.224E+04
ETA2 (PSI SEC)	1.073E+06	9.250E+05	1.021E+06	9.010E+05	1.133E+06	1.149E+06
ETA3 (PSI SEC)	2.098E+07	2.047E+07	1.706E+07	2.143E+07	1.579E+07	1.417E+07
TAU (SEC)	3.000E+01	2.697E+01	2.952E+01	2.762E+01	3.654E+01	3.564E+01
EH (PSI)	2.590E+04	2.120E+04	2.700E+04	2.330E+04	2.484E+04	2.505E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	5.710E-05	7.410E-05	5.320E-05	6.430E-05	5.600E-05	5.640E-05
60 SEC	7.590E-05	9.370E-05	7.320E-05	8.470E-05	7.780E-05	7.790E-05
300 SEC	9.100E-05	1.084E-04	9.110E-05	9.930E-05	9.500E-05	1.002E-04

(*) RESIDUE

(**) MEASURED AT
ROOM TEMPERATURE

FIGURE 31 INITIAL PROPERTIES
OF E SERIES -AE-300

FIGURE 31 CONT.

AB_{ij} = the interaction effect of the i^{th} type of emulsion and j^{th} level of asphalt content.

$\epsilon_{(ij)k}$ = within error.

The calculation of ANOVA was made by means of the SPSS sub-program ANOVA, and the results are shown in Table 28. It must be noted that 8-A and 8-D specimens are not included in this calculation because they do not include any emulsion. Furthermore the restriction error should be included in the model in a strict sense, but it was eliminated assuming that the experiments was conducted in a homogeneous manner.

Figure 31 and Tables 27 and 28 indicate the following:

- 1) With respect to the Hveem Stability S and R, a decrease is found in their values on addition of AE-300. Though the types of the emulsions do not affect the values of S and R, the additional asphalt causes a decrease in the stability values compared with the specimens without the emulsions (8-A and 8-D specimens). The stability values are still at satisfactorily high values.
- 2) The trend in E_1 is similar with both emulsions, while that in E_2 is different. Increase in asphalt content with AE-150 causes a decrease in E_1 and E_2 , but AE-300 tends to raise E_2 in general. E_H is affected by both factors.

Table 28 ANOVA for E Series

Dependent Variable	Type of Emulsion A	Level of Asphalt Content B	Interaction AB
S	-	-	-
R	-	-	-
E ₁	-	**	-
E ₂	**	-	-
τ	**	*	**
η_2	-	-	*
η_3	-	*	-
E _H	*	**	-

** 1% level significant

* 5% level significant

- 3) The viscosities η_2 and η_3 are affected by the amount of asphalt. As the amount of asphalt increases, η_2 decreases, while η_3 increases. Though the fluctuation in the values in η_3 is rather large, AE-300 seem to increase the value of η_3 .
- 4) The retardation time τ is affected by both of the factors and their interactions.

As is clear from the observations above, the difference in types of AE emulsion cannot be found in the Hveem Stability S and R, but can be found in E_2 , E_H and τ . That is, AE-300 seems to raise E_2 , E_H and possibly η_3 , and to lower τ more than AE-150 does. This is an interesting fact, because AE-300 appears to yield much stiffer mixtures than AE-150.

Regarding the mix design, both levels of content of AE-300 residue, i.e., 0.5 percent and 1.0 percent may be used to produce mixtures for a base course, but using them for a surface course material may be difficult because the percent air voids is a little higher than commonly used values (3 to 5 percent). Adding more AE-300 might be a remedy, but taking into account the observation in the process of compaction that bleeding was seen with the specimens with 1.0 percent of AE-300 residue, it would be dangerous to add more AE-300. Different methods of correction, such as adding virgin aggregate and asphalt or heating the mixture, must be sought.

9-3-2 Long-Term Properties — Creep Compliance

The creep behavior of E series using AE-300 was observed every 2 days for the first 15 times of observation, and every 4 days for the next 10 times and then every 6 days for the remaining period up to about 100 days of age. The compliance curves are plotted in Figures 32 (A) and 32 (B).

The following observations are made with respect to the creep compliance:

- 1) At first glance, the two levels of asphalt content show the same trend throughout the observation period and no major difference can be found.
- 2) All of the specimens show a rapid decrease at an early age.
- 3) An increase is found in all of the specimens up to 10 to 25 days of age, and then the compliance curves become almost constant before slowly increasing after about 60 days of age.

Observation 1) indicates that there is little difference produced by levels of asphalt content in all the creep parameters throughout the period.

The increase during 11 to 25 days of age may be the similar phenomenon found with Mobilsol and Reclamite series. In addition to this, a rapid decrease at early ages is also found with the two series. This phenomenon cannot be observed in other series with AE-150

E-1(AP3=0AC, AE-300=0.5)

FIGURE 32 CREEP COMPLIANCE
CURVES OF E SERIES - AE-300

E-2(AP3=0AC, AE-300=1.0)

FIGURE 32 CONT.

or AC-2.5, and particularly is seen in these three series only. As is explained in the last section, this might be caused by delayed softening action.

9-3-3 Long-Term Properties — Creep Parameters

The creep parameters for the series with AE-300 were computed on 19 representative observations. All the values are listed in Appendix B and the average values of the six parameters are plotted in Figures 33 (A) through 33 (F). In the figures, the average values of the two specimens with 0.5 percent of AE-300 residue are plotted in a dotted broken line, and those with 1.0 percent of AE-300 residue are represented by a solid line. A descriptive comparison follows:

- 1) It is commonly seen in all the parameters except for τ that the values increase at a rapid rate, reach very high levels, and are much higher than in #8 series.
- 2) With respect to E_1 , E_2 and E_H , there seems little difference between the two levels of the amount of AE-300 residue as was stated in the previous paragraph. E_1 and E_H clearly reflect the dimple that the creep compliance curve showed during 10 to 25 days of age while E_2 does not. After this, the trend seems almost constant, or even decreasing very slowly. The levels in E_2 are almost the same as those in the 8A-F sub-series.

FIGURE 33 CREEP PARAMETERS OF
E SERIES -AE-300

FIGURE 33 CONT.

FIGURE 33 CONT.

FIGURE 33 CONT.

FIGURE 33 CONT.

FIGURE 33 CONT.

- 3) There is also a difference in η_2 between the levels of the amount of AE-300. The levels of τ are almost the same as those in the 8A-F sub-series.
- 4) Although the amount of AE-300 seems to cause differences in η_3 , the magnitudes of the two are rather high, and in the same level as in the 8M-R sub-series. At about 30 days of age, the values show a decreasing trend as is observed in the R series.

Observation 1) indicates that the reaction rate of AE-300 with the old asphalt may be faster than the reaction rate with AE-150 in the #8 series, and is nearly equal to the rejuvenating agents Mobilsol and Reclamite.

Among the parameters, E_2 and η_2 are found to be at the same level as in the 8A-F sub-series, and η_3 as in the 8G-L sub-series. τ is found to be at the same level as in the 8M-R sub-series. Since the only difference between the 8A-F sub-series and the E series is that of the grade of AE-type emulsified asphalt, and the procession from 8-A to 8-R samples is in the order of increasing amount of AE-150 residue, the observation indicates that E_2 and η_2 show few differences related to the types of the emulsion, while τ and η_3 are affected by the type, or perhaps by the consistency of residues of the agent.

The decreasing trend found in η_3 after about 60 days of age may correspond to the increase in the creep compliance stated in the last paragraph. The phenomenon is the

same as is found with the R series, and this is important since a decrease in η_3 means that the permanent deformation caused by traffic becomes large. Therefore this series also would require further investigation.

9-3-4 Summary

In this section, the initial and the long-term creep behaviors of the recycled specimens with AE-300 are discussed. The following can be pointed out as a summary:

- 1) AE-300 is found to have a higher reaction rate than AE-150, and the resulting recycled mixture seems to have intermediate properties between the properties of mixtures with AE-150 and rejuvenating agents Mobilsol and Reclamite.
- 2) High values of η_3 are found, but they seem to disappear after 2 months, which is just the same situation as was found with Reclamite.
- 3) From the standpoint of mix design, the recycled mixtures may be used as a base course material. Considering the facts that the two levels of content of AE-300 yield specimens which show creep behavior with little difference and that the percent air voids is high, the two levels of content of AE-300 might be on the dry side. However, since the mixtures with 1.0 percent of AE-300 residue added showed bleeding during compaction, adding more AE-300 may be dangerous, and other corrections should be investigated.

9-4 Softening Agent AC-2.5

9-4-1 Initial Properties

A soft grade of asphalt cement has been used as an agent for recycling in some places. Among them is the State of Michigan which has much experience in recycling (1) paved shoulders by mixing heated asphalt cement with 200-250 penetration into unheated pulverized material. In most cases the asphalt cement is heated to as high as 350 F (177 C). Following this process as a model, a soft grade asphalt, AC-2.5, was chosen for use in this study.

The asphalt cement was prepared in the usual laboratory procedure, and heated to 350 F (177 C) in a pan by a direct flame. The temperature control was made by observing the thermometer in the pan, which was also used as a stirring device. During this procedure, heavy smoke was observed. The initial penetration was more than 350 dmm, and it dropped to 245 dmm after the heating.

The original mixtures with the optimum asphalt content (5.4 percent) was artificially weathered to a penetration of 30 and kept at room temperature for several hours. The predetermined amount of AC-2.5 heated to 350 F (177 C) was added to cold mixtures and mixed for 2 minutes with an electric mixer. The mixtures to which 0.5 percent of AC-2.5 was added showed little difference in their appearance from the original mixture and it was not clear if a good coating was obtained or not. The mixtures with 1.0 percent of

AC-2.5 added showed a small degree of cohesion between aggregate particles initially but the appearance became the same as before. Even after one hour in an oven at 140 F (60 C), the mixtures were lacking in cohesion. The mixtures with 0.5 percent of AC-2.5 obviously did not make a good specimen. The cohesive power was not enough so that some of the outer aggregate particles were peeled off after extrusion. This indicates that 0.5 percent is not enough asphalt to recycle highly oxidized mixtures.

The results of the initial tests are shown in Table 29. Some of the properties are plotted in Figure 34. In the figure the results of 8-A and 8-D specimens are also plotted as a basis of comparison. The following are pointed out from the figures and tables:

- 1) The Hveem stability S and R are high compared with other specimens with different softening agents.
- 2) Percent air voids is also high and does not satisfy the required range even for a base course material.
- 3) The creep parameters are almost in the same range as the other specimens, but the retardation time τ seems higher than the others.

As is observed earlier in this section, the specimens with AC-2.5 are not satisfactory, judging from the appearance of the mixture. The observation 1) means that a higher stability value does not always suggest a better mixture,

TABLE 29 INITIAL PROPERTIES OF C SERIES -AC-2.5

ITEM / SPECIMEN	C-1	C-2	C-3	C-4	8-A	8-D
ASPH. CONT.(PCT)	5.4	5.4	5.4	5.4	5.4	5.4
AC-2.5 (PCT)	.5	1.0	.5	1.0	0.0	0.0
STABILITY S(*)	64	59	68	63	63	67
STABILITY R	94	94	94	95	94	94
HEIGHT (IN.)	2.47	2.49	2.56	2.49	2.50	2.47
SP. GR.	2.268	2.273	2.245	2.275	2.255	2.291
AIR VOIDS (PCT)	7.73	6.92	8.67	6.84	8.89	7.43
CREEP PARAMETERS (5 MIN. LOADING)						
E1 (PSI)	2.499E+04	2.221E+04	2.277E+04	2.383E+04	2.072E+04	2.048E+04
E2 (PSI)	3.286E+04	3.018E+04	3.244E+04	3.367E+04	3.102E+04	3.224E+04
ETA2 (PSI SEC)	1.050E+06	9.960E+05	1.191E+06	1.147E+06	1.133E+06	1.145E+06
ETA3 (PSI SEC)	1.746E+07	1.530E+07	1.503E+07	1.784E+07	1.579E+07	1.417E+07
TAU (SEC)	3.195E+01	3.298E+01	3.671E+01	3.407E+01	3.654E+01	3.564E+01
EH (PSI)	2.839E+04	2.559E+04	2.676E+04	2.791E+04	2.484E+04	2.505E+04
CREEP COMPLIANCE (1/PSI)						
10 SEC	4.810E-05	5.370E-05	5.130E-05	4.950E-05	5.600E-05	5.640E-05
60 SEC	6.900E-05	7.610E-05	7.250E-05	6.960E-05	7.780E-05	7.790E-05
300 SEC	8.710E-05	9.720E-05	9.420E-05	8.800E-05	9.900E-05	1.002E-04

0

(*) MEASURED AT
ROOM TEMPERATURE

FIGURE 34 INITIAL PROPERTIES
OF C SERIES -AC-2.5

FIGURE 34 CONT.

and the observation 2) states this series is not satisfactory from the view of mixture properties. In fact no mixtures could be utilized even as a base course mixture as they are. Therefore some remedies in the mixture itself and/or in handling at job sites must be considered. It is reported (1) that the Michigan procedure produces suitable mixtures and that adequate compaction can be obtained. This report mentions that the procedure used in Michigan may be quite different from that used in this study. In conclusion to this paragraph, AC-2.5 is difficult to use as a softening or recycling agent in the manner employed in this study.

9-4-2 Long-Term Properties — Creep Compliance

The creep behavior of C series with AC-2.5 was observed every 2 days for the first 10 times of observation, during which the specimens were found to change very slowly. Then it was observed every 4 days for the next 5 times and every 6 days for the remaining days up to about 100 days of age. The compliance curves are plotted in Figures 35 (A) and 35 (B).

The following observations are made with respect to the creep compliance:

- 1) Similar to the E series, the two levels of asphalt content show the same trend throughout the observation period.

C-1(AP3=0AC, AC-2.5=0.5)

FIGURE 35 CREEP COMPLIANCE
CURVES OF C SERIES - AC-2.5

FIGURE 35 CONT.

- 2) The initial decrease is very slow compared with the 8-A and 8-D specimens and other series, and in 25 days of age, the creep compliance becomes almost constant.
- 3) An increase after a few weeks seems to be found in all the specimens, but the increase is not so conspicuous as it is with the M, R and E series. The second increase after about 60 days which is found in the M, R and E series cannot be seen in this series.

In general, the C series specimens may be said to stiffen at a moderate rate and to have less changes than those with other agents.

9-4-3 Long-Term Properties — Creep Parameters

The parameters for specimens with AC-2.5 were computed on 18 representative observations. All the values are listed in Appendix B and the average values of the six parameters are plotted in Figures 36 (A) through 36 (F). In the figures, the average values of the two specimens with 0.5 percent of AC-2.5 are shown with a solid line. Descriptive comparisons follow:

- 1) The two curves are almost the same for all parameters.
- 2) E_1 increases at a moderate rate up to 20 days of age and reaches a peak. After this it drops and again increases at a slow rate.
- 3) E_2 and E_H show a moderate rate of increase up to about 30 days and then the rate of increase becomes slow.

FIGURE 36 CREEP PARAMETERS OF
C SERIES -AC-2.5

FIGURE 36 CONT.

FIGURE 36 CONT.

FIGURE 36 CONT.

FIGURE 36 CONT.

FIGURE 36 CONT.

- 4) η_2 and η_3 show a very similar pattern to E_2 and E_H .
- 5) τ seems almost constant throughout the observation period.
- 6) Compared with the 8A-F sub-series, the levels of these parameters are almost the same.
- 7) Compared with the E series, the moduli of elasticity are almost at the same magnitude, though the time trend is different. However, the retardation time is much higher and η_3 is much lower than in the E series.

Generally speaking, the C series shows a moderate rate of increase with age for all parameters. This means that the reaction rate of AC-2.5 is slow as compared with other agents.

Since the AC-2.5 is the base asphalt of the AE-300 used here, comparison with the E series makes it clear that the emulsification used in this study produced an agent which acted to increase η_3 and decrease τ in the recycled mixture as compared to that provided by AC-2.5.

AC-2.5 seems to give properties similar to AE-150 as far as the magnitudes of the creep parameters in the long-run are concerned, but the initial rate of increase is slower than that in the 8A-F sub-series which uses AE-150.

9-4-4 Summary

The initial and the long-term creep behavior of the recycled specimens using AC-2.5 were discussed in this

section. The following observations can be noted:

- 1) As far as the long-term creep parameters are seen, AC-2.5 seems to yield recycled mixtures similar to those prepared with AE-150. However, from the standpoint of the percent void ratio, the resultant specimens are not satisfactory.
- 2) The initial increase in all of the parameters except for τ is slow in this series.
- 3) Emulsification employed in this study, which happens to be kindly made by K. E. McConnaughay, Inc., provided the AC-2.5 with a character that gave higher and lower η_3 values in recycled mixtures than the original asphalt.
- 4) The mixtures prepared here may not be used even as a base course judging from the high percentage in voids. Corrections to the mixtures are required, which may be the addition of virgin aggregate and new asphalt or the addition of a small amount of an agent with a softer consistency.

CHAPTER 10

TEST RESULTS — ACCELERATED OXIDATION

10-1 Scope

The last two chapters present the results for specimens which have been aged in the laboratory atmosphere. This chapter describes the results for the specimens which have been aged in ovens. The purpose of this experiment was to determine the long-term trend in properties of the recycled mixtures exposed to accelerated weathering conditions. As was observed in the last chapters, the specimens become stable usually in a few weeks after fabrication when aged at laboratory temperature. This time frame may not be satisfactory from the standpoint of a mix design procedure for recycling, and an accelerated test may be needed. Thus this experiment was conducted to explore the possibility of an accelerated weathering test procedure.

The factor of weathering was varied only by varying the ambient temperature. Two levels of temperature, 105 F (40.6 C) and 140 F (60 C), were selected. 140 F may be the nominal maximum temperature the pavement material may experience normally, and 105 F is the average of room temperature (about 70 F) and 140 F. Two forced-draft type ovens were used; a Precision Model 26 oven was set at

105 F (40.6 C) and a Fisher Isotemp Oven (Junior Mode) was set at 140 F (60 C). Temperature was observed by means of a thermometer attached in the top of each oven.

Two sets of specimens were prepared. The specimens of the first set were made from the original mixtures with the optimum asphalt content after being exposed in the loose state in an oven at 140 F for 15 hours before compaction. The specimens were compacted by the conventional hot procedure (59). No softening agents were added. Therefore, the conditions are the same as those of specimens 4-2 and 4-5. The specimens were four in number; two of them were named the P series and aged in the oven at 105 F and the other two were named the Q series and put in the oven at 140 F. The purpose of this set of specimens was to provide a basis for comparison.

The specimens of the second set were made from the original mixtures with the optimum asphalt content. The mixtures were exposed in the loose condition in an oven at 250 F (121 C) for 15 hours. One percent of AE-150 residue was added to the artificially weathered mixtures in the same process that is described in Chapter 5. Thus the conditions are the same as those of specimens 6-3, 6-6, 8-C and 8-F. The specimens were four in number, two of them were named the L series and aged in the oven at 105 F and the other two were named the H series and aged in the oven at 140 F.

The basic information for these specimens is presented in Table 30.

Both sets of specimens were kept at room temperature after fabrication for one day, and then the initial properties were measured. After this, each set of specimens was put into the appropriate oven (105 or 140 F) for aging.

The creep behavior of the specimens was observed at room temperature. In a preliminary study it was found that it takes about 3 hours for a specimen kept at 140 F (60 C) to cool down to room temperature. Thus, it was decided to take the specimens out of the 105 F (40.6 C) oven 3 hours before testing, and 4 hours before testing for the specimens kept at 140 F (60 C).

This chapter presents creep behavior and creep parameter data for the four series. Discussion then follows using the creep parameter data to compare the set aged at room temperature.

The initial properties of the eight specimens fabricated for accelerated aging were measured and they were found to have almost the same properties as those fabricated to be aged at room temperature. Since it is not the object of this chapter to evaluate the appropriateness of these mixtures as recycled mixtures, comparative description on the initial properties is not made.

Table 30 Basic Information for L, H, P and Q Series with Accelerated Aging

Series	Specimen Notation	Softening Agent	Accelerated Testing Temperature	Original Oxidation	Mixture Asphalt Content	AE-150 (residue) Added* (%)	Virgin Aggregate Added (%)	Total Asphalt Content* (%)
L	L-1, L-2	AE-150	105 F	250 F, 15 hr	OAC**	1.0	0.0	6.4
H	H-1, H-2	AE-150	140 F	250 F, 15 hr	OAC	1.0	0.0	6.4
P	P-1, P-2	-	105 F	140 F, 15 hr	OAC	0.0	0.0	5.4
Q	Q-1, Q-2	-	140 F	140 F, 15 hr	OAC	0.0	0.0	5.4

* Percentage by Total Aggregate Weight

** Optimum Asphalt Content

10-2 Creep Behavior — Accelerated Weathering

10-2-1 Creep Compliance

The creep behavior was observed every day for the first 10 days, every 2 days for the next 10 days and every 4 days afterwards up to about 60 days.

Some of the creep compliance curves are shown in Figures 37 (A) through 37 (D). It must be noted that the scale of the abscissa (age in days) is different from the scale in the curves for the other specimens aged at room temperature. The following observations are made from the figures:

- 1) The L series (AE-150 added, aged at 105 F (40.6 C))

The creep compliance decreases rapidly during the first few days, and in about five days, the curves show an almost flat trend.

- 2) H series (AE-150 added, aged at 140 F (60 C))

Though initial decrease in creep compliance is rapid, fluctuation takes place up to about 20 days of age, after which the trend is stable. The magnitude is almost the same as in the L series.

- 3) P series (no agent added, aged at 105 F (40.6 C))

The rate of decrease in the compliance is large initially, but the decreasing trend seems to continue for a longer time than in the L series. Fluctuation is also found for the first 10 to 20 days.

FIGURE 37 CREEP COMPLIANCE CURVES
OF L. H. P. Q SERIES WITH ACCELERATED
OXIDATION

H-1(AE150=1.0,140F)

FIGURE 37 CONT.

P-1(AP3=0AC,105F)

FIGURE 37 CONT.

Q-1(AP3=0AC,140F)

FIGURE 37 CONT.

4) Q series (no agent added, aged at 140 F (60 C))

The rate of initial decrease in creep compliance is steeper in this series than in P series. Increase is seen after 30 days of age.

As a summary to the observation above, two points are raised:

- 1) The specimens which were aged at 140 F (60 C) tend to show fluctuation and early decrease in the creep compliance.
- 2) The rate of initial decrease in the compliance is higher in the specimens with AE-150 added than those with the original asphalt only.

As a next step, comparison was made between these specimens and the corresponding specimens in the #4 and #6 series in the hope that an equivalent effect of aging at 105 F (40.6 C) or at 140 F (60 C) could be found as compared with the aging effect at room temperature. It was found, however, that it was difficult to obtain such an equivalency because the trends in the creep compliance curves at higher temperature show little similarity with those at room temperature. It can be said that the specimens with AE-150 added reached almost stable conditions in 10 days when the temperature of 105 F (40.6 C) was used. However, such was not the case for the higher temperature of 140 F (60 C).

10-2-2 Creep Parameters

The creep parameters for specimens aged at elevated temperature were computed for the first 15 observations. The values are presented in Appendix B. Though figures are not used to present the parameter data, it can be said that fluctuation is observed to be large compared to the series discussed previously.

In order to compare the results with the series aged at room temperature, the last five observation values were averaged within a cell as are presented in Table 31 and plotted in Figure 38. In Figure 38, the initial values are entered in dotted lines and the estimated values at 100 days of age of the corresponding specimens aged at room temperature in dashed lines. The L and H series are compared to specimens 4-2 and 4-5, while the P and Q series are compared to specimens 6-3 and 6-6. The estimated values at 100 days of age are discussed in Chapter 11 in more detail.

Figure 38 shows the following results:

- 1) All of the parameter values except for η_3 of the P series are between the initial and the 100th day values of the corresponding series.
- 2) Aging at the higher temperature (140 F, 60 C) raises the values of the parameters E_1 and τ , but η_3 shows lower values at 140 F than at 105 F (40.6 C). The behaviors of E_2 and η_2 may indicate the presence of the

Table 31 Average Values of Creep Parameters for L, H, P and Q Series with Accelerated Aging *

Series Parameters	L	H	P	Q
E_1 (psi)	32710	34890	28630	34570
E_2 (psi)	74510	63890	57950	63220
η_2 (psi sec) $\times 10^6$	2.502	2.209	1.751	2.010
η_3 (psi sec) $\times 10^7$	3.247	2.212	3.126	2.752
τ (sec)	33.62	34.87	30.08	31.88
E_H (psi)	45120	45040	38030	44580

* The values are the average values of the last five observations within a cell.

LEGEND

SOLID LINE= L,H,P,Q SERIES

L= WITH AE-150, AGED AT 104F

DOTTED = CORRESPONDING SERIES

H= WITH AE-150, AGED AT 140F

INITIAL VALUES

P= ORIGINAL MIX, AGED AT 104F

DASHED = CORRESPONDING SERIES

Q= ORIGINAL MIX, AGED AT 140F

100 DAYS OF AGE

FIGURE 38 AVERAGE VALUES OF CREEP PARAMETERS FOR L, H, P AND Q SERIES WITH ACCELERATED AGING

interaction of the factor of aging temperature and other factors such as existence of AE-150.

The first observation shows that 20 days aging at higher temperatures does not make the specimens reach the aging level of 100 days at room temperature.

The second observation challenges the assumption that high temperature alone causes accelerated aging. It is true that high temperature appears to affect the values of E_1 and τ , whose significance in evaluating the viscosity of asphalt inside a mixture will be discussed in Chapter 11. But the fact that another important factor η_3 is affected negatively with an increase of temperature may reveal another important point. That is, aging at high or a different temperature from room temperature might affect the physico-chemical properties of asphalt or a blend of asphalt and a softening agent. This is to say that the aging process of asphalt might be somehow different with the level of ambient temperature, but the data so far obtained are not sufficient to warrant further discussion.

As was mentioned earlier, fluctuation in the creep compliance and in the creep behavior is reported. This phenomenon, and the contradicting fact found in η_3 might be partially attributed to the procedure used in this study. As was stated in 10-1, the specimens were taken out of the ovens 3 or 4 hours before performing the creep test

in order that they would reach room temperature. The time is believed to be enough to cool the specimens to room temperature, but it does not guarantee that the asphalt is in a stable condition with respect to component relationships. Even though kinematic movement might have been stabilized to the level of room temperature, the reorientation or the steric hardening referred to in Chapter 2 might not have been completed in a short period. Therefore it is feared that the behavior of each specimen might have been observed while steric hardening was in progress. If this is true, the results of the observations may indicate softer properties than actually existed. Since steric hardening progresses rapidly initially, a small variation in the time after the specimens were taken out of the ovens may have resulted in large fluctuations in the observed values.

Another possible cause for fluctuation and the contradiction with η_3 may be cited. The coefficient of volumetric expansion of asphalt is in the order of 0.00060-0.0063/C (79) and is much greater than that of aggregate. The expansion of asphalt by heat is explained to be a cause of bleeding observed in summer. The same phenomenon takes place inside the ovens and the whole structure of a specimen will be affected by the differential between expansion of asphalt and aggregate. At every time of observation, the result may well fluctuate because of a change in the specimen structure.

The discussion above indicates the difficulty in evaluating the test results conducted at high temperatures. It implies that the period of time that specimens are kept at room temperature must be specified, but even so that the results might be different from those obtained from the specimens aged at room temperature. Terrel and Fritchen report (20) that the resilient modulus measured at 73 F (22.8 C) for the specimen kept at 140 F (60 C) showed large fluctuation and that the reproducibility of the test results was questionable. This may endorse the difficulty of developing an accelerated test at high temperature as discussed above.

The results obtained so far are negative in establishing an accelerated test using high temperatures. But it must be kept in mind that change in temperature is intrinsic to bituminous mixtures in highways, and the testing condition of keeping specimens at room temperature may hardly be realized there. Therefore the results obtained through the experiment conducted at room temperature should be considered to function as a basis of comparison, and the results should be evaluated with such an implication.

10-3 Summary

The purpose of the experiment in this section was to measure properties of the specimens under accelerated conditions. It was found that the results showed fluctuation especially at early ages and that stable conditions

were reached in about 20 days. Therefore keeping specimens in ovens at elevated temperature for 20 days may bring the specimens to a condition representing long-term properties. However, the results were somehow different from those obtained through aging for longer times at room temperature. This may be attributed to the different reaction process at high temperatures, to the procedure taken in this study including the rate of steric hardening, and probably to the differential in expansion of asphalt and aggregate by heat. Furthermore, weathering mixtures in a compacted form was found to be less severe than weathering them in a loose condition. Presumably the difference was due to the difference in surface area exposed to the flow of air.

The results obtained here demonstrate the difficulty in establishing an accelerated test procedure even though its importance is realized.

CHAPTER 11

COMPARISON AND DISCUSSION OF TEST RESULTS

11-1 Scope

Chapters 8, 9 and 10 described the experimental results in terms of the initial physical properties and long-term creep behavior. The properties of the creep parameters were presented descriptively. In this chapter quantitative comparison of the parameters is made using regression analysis.

In the previous chapters, many observations were discussed in a descriptive manner rather than in a quantitative way. In this chapter, two such observations are discussed: the first observation relates to the rate of change of η_3 with age. This is considered to be important because the rate seems to be related to the softening effect of the agents used in recycled mixtures; the second observation is that there seems to be some relationship between the Hveem Stability S and R and the creep parameters. This is also important because this relationship may relate the design parameters to the mixture properties given by the creep parameters.

11-2 Quantitative Comparison of Creep Parameters

11-2-1 Estimation of Values at 100 Days of Age

As is clear from the figures presenting long-term trends of the creep parameters in the previous chapters, the long-term trends include many fluctuations probably caused by a mixture property itself and many probabilistic factors involved in the measurement method. Nevertheless, each parameter seems to have a certain trend with age as were described in the paragraphs on the long-term behavior of the creep parameters. When the findings are reviewed, the following two points may be noted:

- 1) The retardation time τ does not show a sudden increase initially and seems to be almost constant throughout the observation period. Fluctuation is large with some specimens.
- 2) Other parameters, E_1 , E_2 , η_2 , η_3 and E_H show a rapid increase in the first few days or weeks and afterwards seem to keep increasing at slower rates. Fluctuation in data is also sometimes large.

The purpose of the study here is to find if the above statements are true, and if so, what kind of factors are involved in the long-term trend of these parameters.

Before proceeding to the analysis, it must be noted that the amount of data generated from the long-term behavior observations is quite large: each specimen has

six parameters which were computed for about 18 to 20 observations. Since there are some 70 specimens, the amount of congregated raw data is of the order of 10000 pieces.

Considering the two findings and the complexity of the data, it was decided to compare the data between the initial values and the estimated values at an appropriate age as a first step of the comparison. To estimate the values at a certain age, a simple linear regression equation in the form of Eq. (11-1) was used (80):

$$y_{ij}^k = \beta_{0i}^k + \beta_{1i}^k T_{ij} + \epsilon_{ij}^k \quad (11-1)$$

where $i = 1, 2, \dots$ the number of specimens

$j = N-7, N-6, \dots$ to N . N being number of total observations in a series

$k = 1, 2, \dots, 6$ the number of creep parameters

y_{ij}^k = the coded values of k^{th} creep parameter on the j^{th} observation of the i^{th} specimen

T_{ij} = the age of the i^{th} specimen at the j^{th} observation

ϵ_{ij}^k = independent error term, $N(0, \sigma^2)$

$\beta_{0i}^k, \beta_{1i}^k$ = parameters to be determined through the least square method for the k^{th} creep parameter on the i^{th} specimen

In the calculation of the parameters β_0^k and β_1^k , all the data were not used. The last eight observations were taken into account considering the fact that those data represent long-term behavior and exclude the first rapid increase. The 100th day of age was selected as the basis

for comparison in consideration of the fact that the series with softening agents other than AE-150 were observed up to about 100 days of age.

The parameters β_0^k and β_1^k were computed with the least square method using the computer. Then the values of the creep parameters at 100 days of age were calculated with Eq. (11-2):

$$y_i^k = b_{0i}^k + b_{1i}^k \times 100 \quad (11-2)$$

where y_i^k = the estimated value of k^{th} creep parameter in the i^{th} specimen

b_{0i}^k, b_{1i}^k = estimated parameters of β_{0i}^k and β_{1i}^k respectively for k^{th} creep parameter in the i^{th} specimen

Since this procedure is only for prediction, the coefficient of correlation, which is usually used to tell the closeness of the dependent and the independent variables, is not referred to in this study. Actually some parameters show high values of the coefficient of correlation, while the others do not. Calculated y^k 's are listed in Table 32, where the values are presented as the average within the cell. Data on the accelerated weathering (P, Q, H, L series) are excluded from this study.

11-2-2 Regression Analysis of Creep Parameters

The computed values of the creep parameters on the 100th day of age are plotted in Figures 39 (A) through

TABLE 32 ESTIMATED CREEP PARAMETERS AT 100 DAYS OF AGE

SPECIMENS		ESTIMATED CREEP PARAMETERS AT 100DAYS OF AGE					
REPLICANTS		E1	E2	ETA2	ETA3	TAU	EH
(1)	(2)	(PSI)	(PSI)	(PSI SEC)	(PSI SEC)	(SEC)	(PSI)
4-1	4-4	6.194E+04	7.608E+04	2.918E+06	3.045E+07	3.823E+01	6.598E+0
4-2	4-5	5.884E+04	7.005E+04	2.605E+06	2.865E+07	3.707E+01	6.187E+0
4-3	4-6	3.580E+04	5.371E+04	1.769E+06	2.595E+07	3.281E+01	4.234E+0
6-2	6-4	4.351E+04	7.257E+04	2.683E+06	2.833E+07	3.658E+01	5.345E+0
6-3	6-6	4.721E+04	8.091E+04	3.108E+06	3.416E+07	3.780E+01	5.829E+0
6-1	6-5	3.151E+04	5.581E+04	1.964E+06	2.533E+07	3.505E+01	3.989E+0
7-A	7-D	3.720E+04	4.975E+04	1.588E+06	2.755E+07	3.171E+01	4.172E+0
7-B	7-E	3.030E+04	4.696E+04	1.455E+06	2.840E+07	3.087E+01	3.641E+0
7-C	7-F	2.109E+04	3.784E+04	1.017E+06	2.652E+07	2.675E+01	2.695E+0
7-G	7-J	3.709E+04	5.664E+04	1.517E+06	3.923E+07	2.675E+01	4.453E+0
7-H	7-K	3.337E+04	5.279E+04	1.403E+06	3.937E+07	2.658E+01	4.072E+0
7-I	7-L	3.071E+04	5.510E+04	1.353E+06	4.410E+07	2.450E+01	3.925E+0
7-M	7-P	3.099E+04	5.392E+04	1.385E+06	4.287E+07	2.569E+01	3.924E+0
7-N	7-Q	2.972E+04	6.340E+04	1.630E+06	4.995E+07	2.553E+01	4.024E+0
7-O	7-R	2.411E+04	6.393E+04	1.494E+06	5.074E+07	2.333E+01	3.493E+0
8-A	8-D	3.763E+04	7.424E+04	2.918E+06	2.984E+07	3.923E+01	4.976E+0
8-B	8-E	4.301E+04	7.026E+04	2.720E+06	2.886E+07	3.864E+01	5.313E+0
8-C	8-F	3.116E+04	6.032E+04	2.173E+06	2.620E+07	3.606E+01	4.087E+0
8-G	8-J	3.688E+04	6.119E+04	2.018E+06	3.179E+07	3.289E+01	4.586E+0
8-H	8-K	3.178E+04	5.765E+04	1.828E+06	3.174E+07	3.163E+01	4.071E+0
8-I	8-L	3.319E+04	6.121E+04	1.868E+06	3.481E+07	3.051E+01	4.292E+0
8-M	8-P	2.825E+04	6.308E+04	1.751E+06	3.898E+07	2.778E+01	3.889E+0
8-N	8-Q	2.853E+04	6.183E+04	1.696E+06	4.164E+07	2.737E+01	3.890E+0
8-O	8-R	2.921E+04	6.449E+04	1.702E+06	4.323E+07	2.638E+01	4.006E+0
M-1	M-2	3.250E+04	6.517E+04	1.929E+06	3.950E+07	2.980E+01	4.319E+0
R-1	R-2	3.359E+04	5.834E+04	1.866E+06	2.716E+07	3.201E+01	4.250E+0
E-1	E-3	3.533E+04	6.906E+04	2.583E+06	2.857E+07	3.732E+01	4.674E+0
E-2	E-4	3.564E+04	6.578E+04	2.216E+06	3.436E+07	3.375E+01	4.626E+0
C-1	C-3	3.830E+04	6.784E+04	2.598E+06	2.825E+07	3.832E+01	4.902E+0
C-2	C-4	3.740E+04	6.712E+04	2.408E+06	2.681E+07	3.579E+01	4.814E+0

FIGURE 39 COMPARISON OF INITIAL CREEP PARAMETERS WITH THOSE AT 100 DAYS OF AGE

FIGUR 39 CONT.

FIGUR 39 CONT.

(D)
FIGUR 39 CONT.

FIGUR 39 CONT.

FIGUR 39 CONT.

(G)
FIGUR 39 CONT.

39 (F) along with the initial values. Since it was observed in Chapter 8 that some parameters seem to be related to the concentration of a softening agent, a graph of concentration p is presented in Figure 39 (G). From Figure 39 the following observations are made:

- 1) In all of the graphs, all of the parameter values increase from the initial values up to 100 days of age. This means that all of the specimens hardened or stiffened during the 100 days of aging.
- 2) τ is not an exception with respect to an increase of the values. It was noted in Chapters 8 and 9 that τ seemed to be almost constant or increasing slightly with time. Figure 39 (C) clearly indicates this is increasing.
- 3) The concentration p seems to be affecting some of the parameters such as τ . But within a series, the total asphalt content also appears to have an effect, and among the series, the level of oxidation in the original mixtures, the type of softening agent, and possibly the existence of virgin aggregate may also be factors.

Based upon the observation above, it was decided to make an analysis to determine the effect of some of the factors on each creep parameter. The method used here is the multiple linear regression analysis with indicator variables (80). Indicator variables are the variables.

used to quantitatively identify the classes of a qualitative variable, and are basically the same as the levels of factors used in ANOVA. ANOVA is difficult to use in this analysis, though it is not impossible, because some variables to be used here are continuous variables. The independent variables used in the model are: (1) concentration of the agent, (2) total asphalt content, (3) percentage of virgin aggregate, (4) existence of AE-150, (5) level of oxidation, and (6) age. The factor of age was treated in two ways. First, the data of the first day of age and the data of the estimated 100th day of age were computed separately. Secondly, the two sets of the data were combined and the effect of age was investigated. In the analysis, the data of the #4, #6, #7 and #8 were used and the other series with other agents were not employed simply because the number of specimens in these series was not sufficient to compare with the specimens using AE-150.

The mathematical model used is:

$$y_i^k = \beta_{0i}^k + \beta_{1i}^k P_i + \beta_{2i}^k T_i + \beta_{3i}^k A_i + \beta_{4i}^k E_i \\ + \beta_{5i}^k O_i + \beta_{6i}^k D_i + \epsilon_i^k \quad (11-3)$$

where $i = 1, 2, \dots$ the number of specimens

$k = 1, 2, \dots, 6$ the number of creep parameters

y_i^k = the coded values of the k^{th} creep parameter of the i^{th} specimen

P_i = the value of concentration p in the i^{th} specimen

T_i = the value of total asphalt content

A_i = percentage of virgin aggregate; 0, 25 or 50

E_i = the existence of AE-150. When AE-150 is added to the i^{th} specimen, $E_i = 1$; otherwise $E_i = 0$

O_i = the oxidation level. When the i^{th} specimen is made of the original mixture weathered at 140 F (60 C) for 15 hrs, $O_i = 0$; otherwise $O_i = 1$

D_i = the age. When the data are the initial values, $D_i = 0$, and when they are for the 100th day, $D_i = 100$

ϵ_{ij} = independent error term, $N(0, \sigma^2)$

β^k = parameters to be determined through the least square method.

As is clear in Eq. (11-3) no interaction terms are taken into account. It would be possible to do so, but it was not done because the addition of interaction terms would not add to an understanding of general trends in the creep parameters.

The calculation was made by means of the computer using the SPSS subprogram SPSS REGRESSION (81). The subprogram is able to search for a "best" set of independent variables using three optional methods. Here in this study, the stepwise method was used. As the pre-established criterion to include or exclude an independent variable, NSTEPS and TOL were set at default values. FIN and FOUT, the minimum and the maximum F-values to enter or to remove

a variable, respectively, were set at a value of 4.0. This is roughly equal to $F(0.95; 1, 90)$, where 90 is the minimum degrees of freedom in the analysis. The value of $F(0.95; 1, 90)$ corresponds roughly to a level of significance of 0.05 for any single test based on 90 degrees of freedom (80). As a criterion to determine the goodness of fit of regression equation, the coefficient of correlation was employed. With respect to a more detailed discussion on the search for best set of variables, reference should be made to Neter and Wasserman (80).

The results of the regression analysis are presented in Table 33. In Table 33, the entries are the values of the parameters, and double asterisks indicate that the value is significant at 1 percent level, while single asterisks indicate that the value is significant at the 5 percent level.

11-2-3 Comparison and Discussion of Creep Parameters

Table 33 and Figure 39 indicate the following with respect to each of the creep parameters.

1. E_1

Concentration of agents and the total asphalt content affect the trend of E_1 considerably. As the concentration and the total asphalt content increase, E_1 decreases. At the initial time, the existence of AE-150 and oxidation level affect E_1 ; when AE-150 is added, E_1 decreases, and

Table 33 Results of Regression Analysis for Quantitative Comparison of Creep Parameters

(A) Initial Values

Dependent Variable	Concentration P	Total Asphalt Content T	Existence of Aggregate A	Existence of AE-150 E	Oxidation Level O		Constant	Coefficient of Correlation R
E ₁	-13990**	-1982**	-	-1806*	4010**		28710**	0.923
E ₂	16702**	-6066**	-	-	-		62220**	0.489
η_2	-	-136500**	-183200*	-128000*	209700**		1467000**	0.623
η_3	17940000**	-	-	-	-6917000**		20160000**	0.511
τ	-13.05**	-	-	-2.95**	6.59**		28.62**	0.876
E _H	-	-3335**	-97*	-4673**	5731**		40420**	0.868

** 1 percent level of significance

* 5 percent level of significance

(B) At 100 Days of Age

Dependent Variable	Concentration P	Total Asphalt Content T	Existence of Aggregate A	Existence of AE-150 E	Oxidation Level O		Constant	Coefficient of Correlation R
E ₁	-26080**	-7331**	-	-	-		84770**	0.706
E ₂	14000**	-7858**	-183*	-	-		102100**	0.605
η_2	-	-348000**	-18540*	-501430*	1085000**		4022000**	0.837
η_3	64080000**	-3928000**	-308200**	-4760000*	-		49700000**	0.907
τ	-21.06**	-	-	-2.12*	6.42**		34.53**	0.936
E _H	-22510**	-7337**	-	-	6051**		89460**	0.682

** 1 percent level of significance

* 5 percent level of significance

(C) Factor of Aging Included

Dependent Variable	Concentration P	Total Asphalt Content T	Existence of Aggregate A	Existence of AE-150 E	Oxidation Level O	Ages D	Constant	Coefficient of Correlation R
E ₁	-21980**	5148**	-	-	3654**	211**	47970**	0.911
E ₂	-	-5895**	-	-	5712**	307**	62180**	0.885
η_2	-	-250300**	-10370**	-331800**	667100**	11390**	2304000**	0.898
η_3	465200**	-4599000**	-287000**	-	-	137300**	39990000**	0.840
τ	-17.06**	-	-	-2.54**	6.51**	0.046**	29.95**	0.920
E _H	-17620**	-5361**	-	-	4924**	250**	52190**	0.932

** 1 percent level of significance

* 5 percent level of significance

when the original mixture is oxidized to a penetration level of 30, E_1 increases. These factors do not, however, affect the value at 100 days of age. The influence of aging is found to be large, as is seen in Figure 39 (A). Initial effects of the existence of AE-150 and the oxidation level indicate that blending of the agent and oxidized asphalt cement has not been completed, while at 100 days of age, it seems to have been completed.

It was indicated in Chapter 7 that the concentration p is negatively proportional to $\log \log$ of the calculated consistency of the blend. Therefore, the effect of concentration indicates that E_1 is affected by the calculated consistency of the blend. This does not necessarily imply, however, that the blending has been completed; this only means that the average consistency of the blend affects the value of E_1 . As the consistency decreases, E_1 also decreases or the mixture becomes softer.

The total asphalt content is related to the average film thickness of asphalt cement. Therefore the effect of total asphalt content on E_1 is interpreted as the effect of the average film thickness. That is, an increase in the average film thickness tends to decrease E_1 .

2. E_2

The regression analysis is not very helpful in evaluating the parameter E_2 as far as the coefficient of correlation is observed, and other factors including the interactions

of the included factors should be considered. The total asphalt content seems to affect E_2 at all ages. As the total asphalt content increases, E_2 decreases except for the #6 series and the 8M-R sub-series. This fact may indicate that E_2 is mainly related to the average film thickness.

The concentration p affects the values of E_2 for each age, but it does not affect the value when the factor of aging is considered. The concentration is positively related to E_2 , that is, E_2 increases as the concentration increases. This might suggest the existence of the effect of the interaction of p and the total asphalt content. That is, certain combinations of the concentration or the viscosity and the total asphalt content may exist that raise E_2 .

It was found that oxidation level affects E_2 when the factor of aging is taken into account. Though the initial value of E_2 does not show a large difference between the two levels of oxidation, the value at the 100th day of age is larger when the specimens were oxidized to a penetration of 30 rather than being oxidized mildly (Series #6 vs. Series #7) (Figure 39 (B)). This trend is seen also in E_1 and E_H , but the difference is seen to be larger in E_2 than the others.

3. η_2

All the factors except for concentration p seem to affect η_2 . The concentration is the only factor that does

not appear in the table as a significant factor. Then η_2 can be said to be unaffected by the concentration of the agents or the calculated viscosity level of the blend. Other factors contribute explaining the trend of η_2 , but still for the initial values the coefficient of correlation is rather low as compared with the high values at 100 days of age. There may be some other factors which influence the initial values of η_2 .

4. η_3

The creep parameter η_3 is shown to be a significant one. Initially the concentration p and the level of oxidation only are significant with the coefficient of correlation being about 0.5, and much remains to be explained by other factors. On the contrary at 100 days of age, all the factors except the level of oxidation seem to contribute to η_3 .

The concentration p appears in all parts of the Table 33 and its increase causes values of η_3 to increase. This phenomenon is more evident at 100 days of age. Therefore the importance of the role of the concentration should be stressed in explaining the variation of η_3 . Since the concentration is related negatively to $\log \log$ of the calculated viscosity of the blend, η_3 may be said to be negatively correlated to the calculated viscosity of the blend, which was not true with η_2 .

At the initial observation, highly oxidized specimens in the #6 and #8 series show lower values of η_3 , but at 100 days of age, the effect of the level of oxidation no longer appears.

This means that the increase in η_3 in the #6 and #8 series is larger than in the others. Since AE-150 tends to increase η_3 , this fact would imply that the old asphalt (30 penetration) in the original mixture in the #6 and #8 series has been reacted with AE-150 during these 100 days to yield the same level of η_3 as the #7 series (60 penetration).

Upon further consideration of the behavior of η_3 , a contradiction should be found in the above statement. In Chapter 6, it was disclosed that the viscosity of asphalt is positively correlated with the viscosity of mixture η_3 . This means that increase in the viscosity of asphalt causes high values of η_3 . Here in this study, however, η_3 was found to be negatively correlated; i.e., a decrease in the blend consistency causes an increase in the values of η_3 . This is a plain contradiction, and cannot be explained unless an assumption is made that AE-150 is likely to yield high η_3 values even when the blend viscosity is lowered. This contradiction might be deeply concerned with the intrinsic character of AE-150 and calls for further research.

5. τ

The regression analysis seems to explain the behavior of τ fairly well. The concentration, existence of AE-150 and oxidation level are the main factors affecting τ , and appear in all of the three parts of Table 33.

The concentration p decreases the value of τ . Addition of AE-150 also decreases τ . The specimens made from the highly oxidized mixtures show higher values. These are clearly depicted in Figure 39 (E).

6 E_H

Since the parameter E_H is the harmonic mean of E_1 and E_2 , the resultant character is similar to both of them. The total asphalt content affects the values of E_H . Existence of AE-150 also has an initial effect. The oxidation level has an initial effect but its effect disappears at the 100th day of age. The concentration p of the agent does not have an initial effect. This is because of the fact that p is negatively proportional to E_1 while it is positively proportional to E_2 . The averaging process cancels the opposing influences.

7. Other Specimens with Other Agents

The discussion so far has dealt with the samples with AE-150 added. Specimens with other agents should be briefly discussed.

Generally speaking, Mobilsol and Reclamite yield similar trends in the creep parameters as compared to each other, and are similar to AE-150 even though the magnitudes are sometimes different. On the contrary, AC-2.5 shows trends close to the #4 series rather than others. Addition of AC-2.5 tends to decrease η_3 instead of increasing it. This indicates that AC-2.5 has no such function as to raise η_3 . AC-2.5 may be considered to have been added just to bind chunks of pulverized old materials.

11-2-4 Effect of Blend Viscosity

It was found in the last paragraph that the calculated viscosity of the blend might be affecting some of the creep parameters. Possible parameters to be affected are E_1 , η_3 and τ . In order to know the degree of the effect of the blend viscosity, the coefficient of correlation was calculated for the following cases:

- 1) Correlation between the blend viscosity and the parameters
- 2) Correlation between log of the blend viscosity and the parameters
- 3) Correlation between log log of the blend viscosity and the parameters

These three cases were all applied to the set of data of the initial values and the set of data of the estimated values at 100 days of age. The calculated coefficients are

shown in Table 34. Here again the data of the M, R, C and E series were excluded from the analysis. Those series were initially included in the data, but the results were found to be less informative. This indicates that the factor of type of softening agent should have been included. Since the purpose of this study is to know the single effect of the blend viscosity, those factors other than the blend viscosity were simply eliminated.

The following are noted from Table 34:

- 1) E_1 is highly correlated to log of the blend viscosity initially, but in 100 days, the effect becomes small.
- 2) τ is highly correlated to log of the blend viscosity throughout the observation time. The correlation becomes strong as the age progresses, and at 100 days of age.
- 3) E_H shows trends similar to E_1 . This may be because of the closeness of E_H to E_1 .
- 4) η_3 shows only a weak relationship initially but becomes strongly correlated with log log of the blend viscosity, and the trend is negative. That is, an increase in the blend viscosity lowers the value of η_3 .

From the observations above, it may be concluded that τ is the best indicator of the change in the blend viscosity, and secondly comes η_3 . E_1 or E_H may not be used in the long-term basis. In actuality, however, τ was found to

Table 34 Coefficient of Correlation for the Effect of Blend Viscosity

(A) Initial Values

Independent Variable Parameter	Blend Viscosity	log of Blend Viscosity	log log of Blend Viscosity
E_1	0.755	0.838	0.837
E_2	-0.092	-0.236	-0.257
η_2	0.412	0.500	0.277
η_3	-0.354	-0.437	-0.444
τ	0.778	0.798	0.789
E_H	0.653	0.696	0.691

(B) At 100 Days of Age

Independent Variable Parameter	Blend Viscosity	log of Blend Viscosity	log log of Blend Viscosity
E_1	0.409	0.529	0.535
E_2	0.454	0.336	0.310
η_2	0.724	0.708	0.692
η_3	-0.573	-0.793	-0.813
τ	0.816	0.910	0.908
E_H	0.483	0.539	0.536

fluctuate in a very wide range, as has been described in several paragraphs and may not be used. Thus, η_3 should be used as the indicator of the blend viscosity. Though this statement simply states that η_3 is correlated with the blend viscosity, it may well be extended to indicate that η_3 can be used to measure the change of the viscosity of the blends. It must be kept in mind, however, that the contradiction still remains unresolved so that this conclusion can be applied only to the specimens with AE-150 or other agents with similar properties.

11-2-5 Summary

This section dealt with a quantitative comparison of the creep parameters especially of the #4, #6, #7 and #8 series using statistical methods. The creep parameters at 100 days of age were estimated, and comparison was made between the initial values of the parameters and the values at 100 days of age. It was found that the values of all parameters increased with specimen age during the 100 days. Various factors were found to be significant in describing the trends of the parameters. Among them, the concentration p of the agents was found to be very important, and later, $\log$ of the calculated blend viscosity or $\log \log$ of the calculated blend viscosity was found to strongly affect E_1 , η_3 and τ . τ might be the best predictor of the change of viscosity, but unfortunately it is difficult to use due to fluctuation of the calculated value: τ may be

handled only by using statistical procedures. η_3 then is the second best predictor. However, a problem still remains in using η_3 , the problem being that when the calculated viscosity of the asphalt blend decreases, η_3 increases, which is counter to the previous finding that η_3 is positively correlated with the viscosity of asphalt in the mixture. It should be remembered, however, that the softening agents used here, except AC-2.5, were emulsions formulated to have high-float characteristics. This fact may account for the anomaly with respect to the increase in η_3 .

11-3 Rate of Initial Change in η_3

11-3-1 Scope

In the last section it was found that some creep parameters are affected by the concentration of the agent. Among them, η_3 was found to be strongly affected so that η_3 can be taken as representing the change of consistency of the asphalt blend inside a mixture. It was also found in the previous chapters that η_3 decreases during the first observations with some specimens. This reduction was named the initial softening effect. In the meanwhile, other specimens show a very rapid increase in η_3 within a few days after fabrication of specimens. These two phenomena are very important in evaluating recycled mixtures because they are chiefly caused by adding softening agents to old mixtures

and may seldom take place in virgin mixtures. Furthermore, the softening effect is important since it may cause the mix to be unstable if the effect is too severe. The rapid increase is also significant as it might limit construction time in the field. It must be noted that both phenomena are concerned with the length of curing time, and therefore, with the time to keep a paved road closed to traffic after the work.

This section describes the calculation of the rate of the initial change in η_3 first, and a descriptive interpretation follows.

11-3-2 Calculation of Rate of Initial Change

In order to calculate the rate of initial change in η_3 , it was deemed to be proper to take the tangent of the curve depicting the trend of η_3 with age at a certain age. Though the curves of η_3 are of various shapes, parabolic curves may be fitted to the first three observations. The equation of a parabolic curve is given by

$$\eta_3 = b_0 + b_1 x + b_2 x^2 \quad (11-4)$$

where x is the age in days and b_0 , b_1 , b_2 are uniquely determined by using the first three observations. The rate of change in η_3 is given by

$$\rho = \left. \frac{d\eta_3}{dx} \right|_{x=x_0} = b_1 + 2 b_2 x_0 \quad (11-5)$$

where ρ is the rate of the change and x_0 is the age to define ρ .

Though the interval of observation is different with each series, this was not regarded in the calculation and only the three observed values were used regardless of the intervals. It was decided to employ the first day as the age x_0 , because observations were begun on all the specimens on the first day (one day after fabrication). Then, ρ is given by

$$\rho = b_1 + 2b_2 \quad (11-6)$$

The value of ρ for each specimen is given in Table 35, and the average values within a cell are plotted in Figure 40.

In evaluating ρ , it should be noted that negative value in ρ means decrease in η_3 or an initial softening effect, while positive value means increase in η_3 or stiffening. The higher absolute magnitude indicates the more rapid reaction.

In Table 35, the average film thickness of the original mixture and that of the agent in the recycled mixture are also entered. The average film thickness θ is given by Eq. (11-7)

$$\theta = \frac{F}{100 G_b \gamma_w} \quad (11-7)$$

TABLE 35 RATE OF CHANGE IN ETA3

SPECIMENS REPLICANTS		RATE OF CHANGE X10000000 PSI SEC/DAY (AVERAGE IN A CELL)	AVERAGE FILM THICKNESS (MICRON)	
(1)	(2)		ORIGINAL MIXTURE	SOFTENING AGENT
4-1	4-4	.1008	9.15	0.00
4-2	4-5	.0608	11.46	0.00
4-3	4-6	-.0359	14.12	0.00
6-2	6-4	-.0402	11.64	1.26
6-3	6-6	-.2059	11.64	2.53
6-1	6-5	-.2966	11.64	3.79
7-A	7-D	-.2653	11.64	0.00
7-B	7-E	.1144	11.64	1.26
7-C	7-F	.2257	11.64	2.53
7-G	7-J	-.1599	9.15	2.53
7-H	7-K	-.0923	9.15	3.79
7-I	7-L	.2273	9.15	5.05
7-M	7-P	-.3024	6.66	6.32
7-N	7-Q	.0762	6.66	7.58
7-O	7-R	.0673	6.66	8.84
8-A	8-D	.1772	11.64	0.00
8-B	8-E	.1937	11.64	1.26
8-C	8-F	.1034	11.64	2.53
8-G	8-J	.0996	*	*
8-H	8-K	-.0386	*	*
8-I	8-L	.1111	*	*
8-M	8-P	.1614	*	*
8-N	8-Q	.0075	*	*
8-O	8-R	.0438	*	*
M-1	M-2	.2088	11.64	1.57
R-1	R-2	1.1890	11.64	1.59
E-1	E-3	.4337	11.64	1.26
E-2	E-4	.7244	11.64	2.52
C-1	C-3	.1454	11.64	1.25
C-2	C-4	-.0543	11.64	2.49

where G_b is the specific gravity of asphalt or agent, γ_w is the specific gravity of water, and F is the asphalt film thickness factor defined by Kumar and Goetz (54), and is given by

$$F = \frac{a - d}{f} \quad (11-8)$$

where a is the percent asphalt by weight of aggregate in the mix, d is the percent asphalt absorption by aggregates in the mix and f is the amount of kerosene retained. Here in this study F is modified into the form

$$F = \frac{a - P_{ba}}{S} \quad (11-9)$$

where S is the surface area of aggregate given in Table 7 in Chapter 4, and P_{ba} is the absorbed asphalt in percent by weight of aggregate. To estimate P_{ba} , the following relationship is utilized (59).

$$P_{ba} = 100 \frac{G_{se} - G_{sb}}{G_{se} G_{sb}} \quad (11-10)$$

$$G_{se} = \frac{1}{2}(G_{sb} + G_{sa}) \quad (11-11)$$

where: G_{se} = effective asphalt, percent by weight of aggregate

G_{sb} = bulk specific gravity of aggregate

G_{sa} = apparent specific gravity of aggregate

Eq. (11-11) states that the effective specific gravity of aggregate can be calculated as the half of the sum of the

apparent specific gravity and the bulk specific gravity of aggregate. This is only an assumption, but sometimes is done routinely (82). In the calculation of the average film thickness θ for the softening agents, P_{ba} was set to be zero, because the aggregate are already covered with old asphalt cement. The thickness θ was not calculated for the #8 series, because virgin aggregate was added as well as the agent so that absorption of the agent was feared to take place, and because migration of the emulsion was found which would cause variation in the thickness of films.

It must be kept in mind here that the calculation of the film thickness is based upon many assumptions so that the results may be used only to view the general trend.

11-3-3 Analysis of Rate of Change in η_3 Data

As is seen in Figure 40, the trend in ρ seems to vary within each individual series and it was not possible to establish a general model for quantitative analysis. Therefore the quantitative comparison was suspended and descriptive explanation alone was used in this study. The trend in each series is observed as follows:

- 1) #4 Series: The rate of change in η_3 , ρ , in the #4 series, decreases as the total asphalt content increases, even though no agents were added. The only factor conceivable to affect trend is the factor of the film thickness. That is, a thicker film might cause a

softening effect, or, a decrease in η_3 at early ages.

- 2) #6 Series: The same phenomenon is observed in the #6 series as in #4 series. The difference between the two series is that of the viscosity of the original asphalt and the viscosity of the newly added agent.
- 3) #7 Series: The trend in ρ drastically changes in the #7 series. As the total asphalt content increases, the rate of change ρ increases. This is generally seen in all of the sub-series in the #7 series. The 7-A and 7-D specimens have the same proportion as 4-2 and 4-5 specimens, the only difference being the fabrication method. The former were fabricated through the cold process, so that the void ratio is higher than in the #4 series. The 7-A and 7-D specimens indicate a softening effect while the 4-2 and 4-5 specimens do not. The difference in behavior should then be attributed to the difference in void ratio. Other samples in the #7 series have differences from the #6 series in the viscosity of the original mixture and differences from the #4 series in the existence of the newly added agent. As far as the sub-series within the #7 series are concerned, no difference is seen between the sub-series.

When the total asphalt content is equal, the total film thickness is almost equal regardless of the agent added. Therefore in the 3 sub-series, the total asphalt content or the total film thickness of asphalt is considered to be the only factor. That is, the thicker the asphalt film, the more rapid is the rate of change in η_3 .

- 4) #8 Series: This series shows an irregular trend in ρ and no general description is possible. This may be caused by the addition of virgin aggregate and agent, and migration of the agent. However, specimens 8-A through 8-F do not have any virgin aggregate and can be compared with the #6 series. A large difference is seen between the 8A-F sub-series and the #6 sub-series, i.e., no initial softening effect is taking place in the 8A-F sub-series. The only difference that exists is the fabrication date, but this fact is not useful in explaining any difference.
- 5) M and R series: The R series shows the highest rate of change in η_3 . This apparently is due to the nature of Reclamite.
- 6) E series: The E series may be compared with 7-B, 7-E; 7-C and 7-F specimens. The general trend is very similar, the difference being the higher ρ value in the E series. This may have been due to the lower viscosity of AE-300.

- 7) C series: The C series shows a trend similar to the #6 series. That is, a higher total asphalt content causes a softening effect.

11-3-4 A Conceptual Model

The review of these results suggests a conceptual model in which a layer of softening agent is inserted between two layers of asphalt film covering aggregate, as is shown in Figure 41. The conceptual model may be used to some extent in explaining the rate of change of η_3 previously reported in Section 11-3-3 by employing the concept of the relative magnitude of viscosity as follows:

- 1) In the #4 series, no softening agent was added but the amount of asphalt varied providing an increase in film thickness. The absolute viscosity of the asphalt is about 2000 poises, which is not high as compared to that in the heavily oxidized mixtures. When a load is applied to the specimen, a shearing stress acts to shear the layer of asphalt between the two aggregate pieces. Since the central part of the layer may well be soft as compared to that portion adsorbed onto the surface of the aggregate, the amount of strain produced by a load will be influenced by this softer layer. Some time after fabrication, even though the central part of the layer may become harder presumably due to time hardening or other causes of hardening referred to in Chapter 2, the strain produced

FIGURE 41 CONCEPTUAL
MODEL TO EXPLAIN RATE
OF CHANGE IN η_{a3}

by the same load will be less than before. As the thickness of the layer becomes large, the slippage will occur more easily, and this may be the reason for the decrease in ρ with an increase of the total asphalt content.

- 2) In the #6 series, the asphalt film of the original mixture has a very high viscosity compared with the viscosity of the softening agent, which is almost 1/70 of the former. With highly oxidized asphalt, time is required for the softening agent to redisperse the asphaltenes. When a load is applied to the specimen, the shearing stress may easily shear the low viscosity layer of the softening agent, which causes easy movement. There still remains a problem in that the second observation shows a higher strain than the first. This may be explained as follows: the initial strength is due to the interlocking of aggregates. In a short period of time, the softening agent begins to redisperse the asphaltenes at the interface of the two layers. This interface might be weaker than or as weak as the central part, and movement might take place here at the interface as well as at the central part. As the amount of the softening agent increases, an increased region of weakness will occur, and a softening may result.

- 3) In the #7 series, the viscosity of the original asphalt is about 2000 poises while that of the softening agent is about 100 poises: thus, the difference is not as large as in the #6 series. Furthermore, the original asphalt has not been oxidized to the point that it will take a long period for the agent to redisperse the asphaltenes in the oxidized asphalt, and eventually the blend becomes rather homogeneous. It must be remembered that AE-150 tends to raise η_3 probably due to its thixotropic character. The higher content of the agent causes the higher increase in η_3 , while the thicker layer of the agent still causes slippage and the two effects offset each other to yield almost the similar distribution of ρ among the sub-series. With respect to the difference between the 7-A and 7-D specimens and the 4-2 and 4-4 specimens, the large void ratio in the former may be the clue. The higher void ratio means the less points of contact among the aggregates. Considering the load applied to the specimens, the level of the shear stress at the contact point is larger than that in specimens with a small void ratio. This concentration of stress causes easy movement at the interface or at the central part of the agent resulting in a decrease in η_3 .
- 4) The high rate of increase of η_3 in the M and R series may be explained in the same way as in the #7 series.

Although the relative magnitude of the viscosities of the original asphalt and the rejuvenators, Mobilsol and Reclamite, are large as compared to AE-150, the reaction rate is much faster with the two rejuvenators.

- 5) The situation in the E series using AE-300 may be the same as in the M and R series.
- 6) The rate of increase in η_3 , ρ may be the same in the C series as in the #6 series may be expected to take place.

As is stated above, the conceptual model can explain the rate ρ of change in η_3 to some extent. The #8 series using virgin aggregate, however, presents difficulty in explaining the variations in ρ , and this must be resolved by further investigation.

11-3-5 Summary

This section presented the rate of change in η_3 at the initial ages. The initial softening effect and the early increase in η_3 were expressed as the negative and positive values of the rate ρ , respectively. Although a quantitative model could not be established, a conceptual model was presented that could be used to explain variation in the rate. Only the results of one series could not be explained

by the conceptual model and further investigation is required.

If the conceptual model can be assumed to be valid, the following points are now clear:

- 1) When the difference in viscosity between the asphalt in the old mixture and the softening agent is large and when the dispersing power of the agent is weak an initial softening effect may take place. The magnitude of the effect is proportional to the total bitumen content.
- 2) When the difference in viscosity between the old asphalt and the softening agent is small, the initial softening effect may not occur.
- 3) The commercially available rejuvenating agents with strong dispersing power used in this study, provided a rapid increase in η_3 , and eliminated the softening effect.

The first point is the most important to be kept in mind when designing recycling mixtures. When the material is suspected to contain highly oxidized asphalt, it is recommended that a test be performed to find if the initial softening effect will take place, by adding some amounts of the agent in different percentages to the old material and by conducting a stability test or the creep test preferably over a period of a few weeks.

11-4 Viscoelastic Interpretation of the Hveem Stability

11-4-1 Scope

The Hveem stability values R and S are widely used as criteria for the design of bituminous mixtures. It was observed by Tia et al (22) that repeated testing on the same specimen with the stabilometer is not possible since R and S values showed increases in values at repeated testing. In pursuing the long-term change in recycled mixtures, however, it would be convenient if the stability values could be used to measure change. It is true that the changes in mixtures can be determined through the creep parameters as actually done in this study, but since they are not directly related with any criteria for designing mixtures, it was thought to be worthwhile to investigate the relationships between the Hveem stability values and the creep parameters. It will be disclosed in the course of discussion that follows that the stability S measured at 140 F (60 C) in the standard procedure is highly related to a theoretical model including the creep parameters, while the stability S measured at room temperature (70 F, 21.1 C) and the stability R are best related to the modulus of elasticity, E_1 .

Hveem described in his discussion for the usage of the stabilometer that the results of the stabilometer test depend almost entirely on internal friction of the mass and are influenced to only a slight degree by the so-called cohesion, or the viscous resistance of the binder (83). This description indicates that he implicitly considered the mixtures

to be viscoelastic. Therefore it is thought to be possible to analyze the stabilometer results in terms of viscoelasticity. It is true that Hveem Stability R and S are quite empirical and their scales are arbitrary rather than theoretical. Therefore there may be various ways to interpret the R and S values. Viscoelastic interpretation is only one of them.

This section discusses theoretical considerations using viscoelasticity first, and then presents the results and conclusion.

11-4-2 Viscoelasticity Considerations with the Hveem Test

The Hveem Stability Test may be classified as a modified tri-axial test (84). As a first approximation, however, the test may be taken as a uni-axial test. Here in this study, this approximation is employed. Since the Hveem Stabilometer Test is conducted under the constant rate of deformation, 0.06 in/min or 0.212 cm/sec, this test is classified as the case of the constant rate of deformation according to Alfrey's classification (48) described in Chapter 2.

In viscoelastic materials, the stress as a function of time is represented through a superposition integral involving the strain history $\epsilon(t)$ and the relaxation function $G(t)$. The stress $\sigma(t)$ is given by Eq. (11-12):

$$\sigma(t) = \int_{-\infty}^t \frac{\partial \epsilon(\tau)}{\partial \tau} G(t-\tau) d\tau \quad (11-12)$$

where t is time. The strain history $\epsilon(t)$ is given for this case by,

$$\epsilon(t) = rt \quad (11-13)$$

where r is the rate of strain increment per unit time and can be expressed with the height h of the specimen as

$$r = 0.00212/h \text{ (cm/cm-sec)} \quad (11-14)$$

where h is given in centimeters.

As the model for this analysis, the Burgers Model can be used, but as will be shown below, the analysis is complicated so that a simpler model, the Maxwell Model, is also discussed. The relaxation functions $G(t)$ for the Maxwell Model and the Burgers Model are given by Eqs. (11-15) and (11-15) respectively:

$$\left. \begin{aligned} G(t) &= E \exp(-t/\tau_0) \\ \tau_0 &= \eta/E \end{aligned} \right\} \quad (11-15)$$

$$\left. \begin{aligned} G(t) &= C_1 \exp(-t/\tau_1) + C_2 \exp(-t/\tau_2) \\ C_1 &= -E_1 \frac{1/\tau_0 - 1/\tau_1}{1/\tau_1 - 1/\tau_2} \\ C_2 &= E_1 \frac{1/\tau_0 - 1/\tau_2}{1/\tau_1 - 1/\tau_2} \\ \tau_0 &= \eta_2/E_2 \end{aligned} \right\} \quad (11-16)$$

τ_1 and τ_2 are the solutions of the equations:

$$\frac{1}{\tau_1} + \frac{1}{\tau_2} = \frac{E_2}{\eta_2} + \frac{E_1}{\eta_2} + \frac{E_1}{\eta_3}$$

$$\frac{1}{\tau_1 \tau_2} = \frac{E_1 E_2}{\eta_2 \eta_3}$$

In Eq. (11-15), E is equivalent to E_H and η to η_3 as is described in Chapter 6. Taking into account that the specimens are not loaded until $t=0$, the strain $\sigma(t)$ is given for the two models by:

$$\text{Maxwell: } \sigma(t) = r\eta\{1 - \exp(-t/\tau_0)\} \quad (11-17)$$

$$\begin{aligned} \text{Burgers: } \sigma(t) = r [\eta_3 - \{C_1\tau_1 \exp(-t/\tau_1) \\ + C_2\tau_2 \exp(-t/\tau_2)\}] \end{aligned} \quad (11-18)$$

Eqs. (11-17) and (11-18) are the stress function of time t . Eliminating t from the two equations using Eq. (11-13), the stress-strain relationship is derived:

$$\text{Maxwell: } \sigma = r\eta_3\{1 - \exp(-\frac{\epsilon}{r\tau_0})\} \quad (11-19)$$

$$\begin{aligned} \text{Burgers: } \sigma = r [\eta_3 - \{C_1\tau_1 \exp(-\frac{\epsilon}{r\tau_1}) \\ + C_2\tau_2 \exp(-\frac{\epsilon}{r\tau_2})\}] \end{aligned} \quad (11-20)$$

The Equations (11-19) and (11-20) indicate that the stress-strain relationship is non-linear.

It is a well known fact in dealing with non-linear materials that some types of "modulus of elasticity" are defined to describe non-linear elasticity (85). The initial modulus of elasticity, the secant modulus of elasticity and the tangential modulus of elasticity as are shown in Figure 42 are the examples. In a preliminary study with the #4 series, it was found that the tangential modulus of elasticity E_t is closely related to the stability S , so that E_t is used hereafter.

The tangential modulus of elasticity E_t at a specified time t_0 is given by taking the first derivative of the stress function with respect to the strain. For the Maxwell Model,

$$E_t = \left. \frac{d\sigma}{d\varepsilon} \right|_{\varepsilon=\varepsilon_0} = E \exp(-t_0/\tau_0) \quad (11-21)$$

For the Burgers Model,

$$E_t = C_1 \exp(-t_0/\tau_1) + C_2 \exp(-t_0/\tau_2) \quad (11-22)$$

Comparing the two equations with (11-15) and (11-16), it is found that E_t is nothing but the relaxation function at $t=t_0$. It should be noted that the initial modulus of elasticity is given by putting $t=0$ into the two equations. For the Maxwell Model, the initial modulus is E and for the Burgers Model it is E_1 .

FIGURE 42 TYPES OF
MODULUS OF ELASTICITY

In the process of the stabilometer test, the stress levels are given to calculate the stability values; $\sigma_0 = 400$ psi for S value and $\sigma_0 = 140$ psi for R value. The time for the stress level σ to reach the specific value σ_0 can then be computed by solving the equation for t :

$$\sigma(t) = \sigma_0 \quad (11-23)$$

In the Maxwell Model, Eq. (11-23) can be solved algebraically and t_0 is given by

$$t_0 = -\tau_0 \ln\left(1 - \frac{\sigma_0}{\gamma\eta}\right) \quad (11-24)$$

In the Burgers Model, however, Eq. (11-23) cannot be solved algebraically and requires a numerical solution. The solution may be obtained by solving the equation for $t = t_0$:

$$\begin{aligned} \sigma(t_0) = r[\eta_3 - \{C_1\tau_1 \exp(-t_0/\tau_1) \\ + C_2\tau_2 \exp(-t_0/\tau_2)\}] = \sigma_0 \end{aligned} \quad (11-25)$$

In the process of calculation, the Newton-Raphson Method was utilized (68).

11-4-3 Results of Tangential Modulus of Elasticity Calculations

The tangential modulus E_t was calculated for the two stress levels, $\sigma_0 = 160$ psi (11.2 kg/cm²) and 400 psi

(28.1 kg/cm²), for the two models using the initial values of the creep parameters of all specimens. The calculated values are shown in Table 36.

A linear regression analysis was made between the stability values and E_t . The summary is given in Table 37. Entries in Table 37 are the coefficients of correlation. In the analysis, comparison was also made between the stability values and the creep parameters. The model used here is given by

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i \quad (11-26)$$

where Y_i = stability R or S in the i^{th} specimen
 X_i = independent variable in the i^{th} specimen
 β_0, β_1 = parameters
 ϵ_i = a random error term

Before interpreting the results, these points must be kept in mind:

- 1) The creep parameters are all measured at room temperature.
- 2) Only a linear model with a single dependent variable is used.
- 3) The number of data for the S value at 140 F is only 6, and all of them are in the #4 series.
- 4) No factors other than each independent variable are taken into account in the analysis.

TABLE 36 CALCULATED TANGENTIAL MODULUS
OF ELASTICITY

SAMPLE	HUEEM STABILITY R S	TANGENTIAL MODULUS OF ELASTICITY (PSI)		SAMPLE	HUEEM STABILITY R S	TANGENTIAL MODULUS		OF ELASTICITY (PSI)	
		BURGERS MODEL E(160) E(400)	MAXWELL MODEL E(160) E(400)			BURGERS MODEL E(160) E(400)	MAXWELL MODEL E(160) E(400)		
4-1	* 42	14650	11870	8-E	94 57	12520	10070	22007	20391
4-2	* 44	14470	12600	8-F	94 67	10870	9150	19538	18443
4-3	* 37	9850	8910	8-G	93 52	10830	9810	20281	19657
4-4	* 41	14270	11320	8-H	91 43	8930	8200	17160	16465
4-5	* 43	14030	12000	8-I	91 50	9900	8970	18824	18032
4-6	* 36	10720	9640	8-J	92 58	9750	8520	18252	17180
6-1	93 55	10300	9470	8-K	93 61	9070	8230	17263	16541
6-2	93 48	10710	9840	8-L	91 47	6840	5900	13462	11967
6-3	93 57	11230	10280	8-M	92 53	9140	8620	17885	17275
6-4	94 50	11930	10350	8-N	91 48	8880	8360	17314	16766
6-5	91 42	9140	8500	8-O	91 49	9200	8780	17965	17575
6-6	93 51	10900	10090	8-P	89 44	9120	8570	17854	17194
7-A	92 55	11040	10210	8-Q	90 48	8760	8310	17140	16653
7-B	91 39	7420	6920	8-R	89 42	7600	7000	14886	14059
7-C	88 36	7460	7100	M-1	91 51	12600	11180	23295	22434
7-D	92 60	9250	8700	M-2	92 52	12710	11210	23302	22480
7-E	92 51	7830	7240	R-1	93 61	10690	9590	20315	19297
7-F	89 36	5370	5100	R-2	92 47	9110	8280	17712	16653
7-G	92 44	9240	8680	E-1	93 51	14170	12210	25308	24416
7-H	88 37	9400	8980	E-2	92 55	10900	9950	20701	19952
7-I	91 41	6550	6280	E-3	93 54	15050	12550	26254	25132
7-J	89 36	10370	9830	E-4	93 54	12350	10980	22787	22014
7-K	89 38	7670	7330	C-1	94 64	16550	13260	27618	26461
7-L	85 26	5630	5310	C-2	94 59	14480	11770	24792	23592
7-M	94 60	9240	8960	C-3	94 68	15500	12320	25881	24568
7-N	89 40	6840	6650	C-4	95 63	16290	13100	27162	26040
7-O	75 17	7390	7140	P-1	93 63	9550	8650	18084	17380
7-P	89 38	8090	7820	P-2	94 64	12100	10770	22422	21620
7-Q	88 33	9090	8770	Q-1	94 62	9860	8850	18535	17790
7-R	84 24	5560	5360	Q-2	93 57	11900	10460	21570	20962
8-A	94 63	14150	11500	H-1	92 41	11330	9600	20423	19339
8-B	94 55	13700	11500	H-2	93 48	11410	9740	20825	19651
8-C	94 58	10520	8800	L-1	93 62	13660	11950	24911	23987
8-D	94 67	14120	11490	L-2	93 43	11630	10110	21183	20296

E(160): Modulus at $\sigma = 160$ psiE(400): Modulus at $\sigma = 400$ psi

Table 37 Summary of Regression Analysis for the Hveem Stability

Dependent Variables		Stability Values		
Model	σ_0 (psi)	S (140°F)	S (70°F)	R (70°F)
E_t	160	-	-	0.7303
	400	0.9306	0.6695	-
	160	-	-	0.7268
	400	0.9650	0.6667	-
E_1^*	-	0.8769	0.7093	0.7737
E_2	-	0.9382	0.1042	0.0708
τ	-	0.3619	0.6133	0.6954
η_2	-	0.8225	0.4645	0.4850
η_3	-	0.0724	-0.2623	-0.2895
E_H^{**}	-	0.9088	0.6919	0.7399
Number of Data		6	61 [†]	61 [†]

* Corresponding to the initial modulus in the Burgers Model

** Corresponding to the initial modulus in the Maxwell Model

† Sample 7-0 excluded

With these limitations in mind, the following comments are presented:

- 1) With respect to the stability value S measured with the standard procedure for the #4 series, the tangential modulus of elasticity E_t at $\sigma_0 = 400$ psi (11.2 kg/cm^2) using the Burgers Model indicates the highest correlation with S .
- 2) With regard to cold processed mixtures, the first modulus of elasticity is best correlated to R and S measured at room temperature, though the correlation coefficient is not so high as in the #4 series.

The observation above may be summarized to say that mixtures may exhibit viscoelastic behavior at 140 F (60 C) much more than at 70 F (21.1 C), and that, at room temperature mixtures can be regarded as an elastic body as far as the Hveem stability is concerned. Though this is not discussed here, the rate of deformation is considered to affect the results. If the rate of deformation had been more rapid, the viscoelastic character might have revealed itself.

The stability R , which has been chiefly used in the discussion of the initial properties, was found to be most closely correlated to E_1 . However, the correlation coefficient is not high, and the correlation cannot be said to be explained completely. As is mentioned above, a single variable might not be enough, and a more sophisticated model

such as a polynomial form, or other factors might be incorporated in the regression equation. This is, however, beyond the cadre of this research, and should wait for further investigation.

11-4-4 Summary

In this section the Hveem Stability R and S were analyzed using viscoelastic models. The S value measured with the standard procedure is found to be highly correlated with the tangential modulus of elasticity with viscoelastic properties incorporated. The R value and the S value measured at room temperature is found, however, to be correlated with the modulus of elasticity alone. This may be attributed to the very slow rate of deformation employed in the Hveem Stability Test and to the dominance of the elastic property of mixtures over the viscoelastic property at room temperature. It must be borne in mind that the regression analysis is of only one order and other factors are not taken into account.

Since the results indicate that the R value is correlated to E_1 , and the correlation coefficient is not high, the estimated R and S values were not employed in this study.

CHAPTER 12
SUMMARY OF RESULTS, RECOMMENDATIONS
FOR A DESIGN PROCEDURE, AND CONCLUSIONS

12-1 Review of the Study

This study described the long-term effects of softening agents on recycled mixtures produced in a cold process.

First, a conceptual diagram of the long-term behavior of recycled mixtures was proposed in which the concept of the viscosity of mixture was introduced. The reaction of a softening agent with an old asphalt was explained schematically and the existence of thin layers with different viscosities was predicted.

Next, literature was reviewed and it was found that while recycling was becoming widely used there still were many questions that were unsolved. In general, there seems to be two concepts in the recycling practice; one of them is that asphalts are to be added to old mixtures to reunite the pulverized old materials, and the second is that the consistency of the old asphalt is to be reduced to a certain level by adding commercially available rejuvenating agents. Design procedures were different in the two

concepts. The first usually employed a convention mix design method, while the second used a blending curve. The two concepts seem to have been treated separately.

Based upon the conceptual model and the literature review, an experiment was set up to observe long-term behavior of recycled mixtures. Softening agents, AE-150, AE-300, AC-2.5 and two rejuvenating agents, Reclamite and Mobilsol were used. As an index of the long-term behavior it was decided to utilize creep parameters as obtained from a creep test and the Burgers Model, and some basic studies were made to observe creep behavior of mixtures.

In the course of the experiment, blending curves for various agents used in this study were drawn and it was discovered that a functional relationship existed between the concentration of the agents and the viscosity of the blends irrespective of the type of agents used.

The initial and long-term behavior of recycled mixtures were reported. The effectiveness of the agents was discussed from the standpoint of the mix design using the initial properties. The long-term properties were compared among the specimens with different agents by means of Burgers Model parameters and statistical procedures. The viscosity of mixture, η_3 , and the calculated viscosity of the blend of oxidized asphalt and softening agent were shown to be strongly related. During the observations,

it was found that some specimens showed an initial softening effect at early ages. To explain this effect, a conceptual model was developed using the rate of change in η_3 . Also, the relationship between the Hveem Stability R and S and the creep parameters was discussed.

Finally the results obtained in the accelerated weathering test were presented. Comparison of these with the results for specimens aged at room temperature showed that the accelerated test procedure produces a different reaction inside the mixture, and a direct comparison of the two weathering procedures is difficult.

12-2 Summary of Results

Based upon the experiments conducted in this study, the following summary is presented.

12-2-1 The Usefulness of the Softening Agents

The usefulness of the softening agents was examined from the standpoint of initial mixture properties, and the following points are presented:

- 1) When the original mixtures to be recycled were mildly weathered, AE-150 produced mixtures that could be used even as a surface course material.
- 2) When the original mixtures were strongly oxidized, AE-150, AE-300, Reclamite and Mobilsol produced mixtures that could be used as base course material; however, an initial softening effect may take

place which could affect early stability of the mixture.

- 3) AC-2.5 is difficult to use as a recycling agent for heavily oxidized materials. AC-2.5 seems to have the effect of only binding the old oxidized materials together.
- 4) The softening agents might be used to produce a surface course material with the heavily oxidized mixtures, when the virgin aggregate and virgin asphalt sufficient to cover the virgin aggregate and to soften the old mixtures are added.

12-2-2 Blending Curve

- 1) In using the rejuvenating agents, Mobilsol and Reclamite, blending curves were used to determine the amount of the agents to obtain a target viscosity of the blend. The target viscosity, however, did not always give a favorable mixture property, because the target viscosity was arbitrarily determined. Therefore it is dangerous to determine the amount of the agents solely by the blending curve; a mix design procedure is required.
- 2) From the experimental results with the blending curve, a functional relationship was found to exist between the concentration of an agent and the blend viscosity irrespective of the type of the agents used. This indicates that there is no intrinsic

difference in the agents with respect to the function to reduce the viscosity of the old asphalt.

12-2-3 Initial Softening Effect

Based upon a conceptual model using the film thickness and relative magnitudes of the viscosities of the old asphalt and the agent, the following summary is made:

- 1) When the difference in viscosities is large and when the dispersing power of the agent is small, an initial softening effect was present.
- 2) When the difference in viscosities is small, the initial softening effect may not occur.
- 3) Commercially available rejuvenating agents used in this study, show a rapid reaction with the old asphalt and the initial softening effect did not occur.

12-2-4 The Long-Term Properties

The comparison of the long-term properties using the Burgers Model and statistical procedures produced the following results:

- 1) The calculated viscosity of the blend was found to play an important role in producing mixture properties. This factor was especially conspicuous in the retardation time τ and the mixture viscosity η_3 . This factor becomes more important

as the age progresses, and the blend becomes more homogeneous.

- 2) AE-150, AE-300 and the two rejuvenating agents used in this study had a tendency to increase η_3 and lower τ , while AC-2.5 does not. A high value of η_3 is favorable because the permanent deformation induced by load is small. Attention should be paid, however, to the behavior of η_3 when AE-150 and AE-300 are used. Usually η_3 is considered to be positively correlated to the viscosity of asphalt in the mixture. The results with η_3 indicate a negative correlation for these materials, which may be due to their specific high-float nature. Furthermore, some specimens with AE-300 and Reclamite developed a decrease in η_3 after two months, which should also be heeded.
- 3) Other parameters than τ and η_3 seem to be affected by the blend viscosity, but other factors may have stronger effects on them. E_1 , the modulus of elasticity in the Maxwell Model is strongly affected by the calculated blend viscosity at the initial observation, but the effect seems to be weakened in later days.

12-2-5 The Creep Test and Viscoelasticity

- 1) The creep test employed in this study proved to be very effective in describing mixture properties. The creep compliance is not useful when it is used

alone, however. Viscoelastic analysis must be included and the creep parameters must be computed.

- 2) The Hveem Stability R and S were interpreted by the theory of viscoelasticity using the creep parameters. It was found that S values determined at the standard temperature of 140 F (60 C) are correlated with viscoelastic models, while R values and S values measured at room temperature were related to the modulus of elasticity.

12-2-6 Miscellaneous

- 1) With respect to the properties of old mixtures, two points must be kept in mind. First, the old mixtures, especially heavily oxidized ones, tend to produce large chunks, which may cause insufficient dispersion of softening agent. Second, when virgin aggregate is introduced to the old mixtures, migration of the agents may take place from the virgin aggregate to old mixtures, and this causes insufficient coating on the virgin aggregate.
- 2) A conceptual model that the highly oxidized portion of asphalt may be inert and considered as part of the aggregate was not proved.
- 3) The conceptual model given in Figure 1, Chapter 1, indicates the possibility of establishing maximum

and minimum limits for η_3 . This could not be accomplished in this study, partially because the particular character of AE-150 raised the value of η_3 even when the blend viscosity was lowered.

- 4) The accelerated weathering test procedure used in this study did not produce the same results as those that occurred with time at ambient temperature.

12-3 Recommendations for a Design Procedure

With the summary stated previously as the basis, the following recommendations for a design procedure are presented:

- 1) For design purposes, the importance of the calculated viscosity of the blend should be stressed. It was found in the study that the viscosity of asphalt in the mixture controls the creep parameters, and therefore the mixture properties. Thus, in designing the recycling mixtures, the blend viscosity should be specified as a design criteria. This will be understood to be reasonable when one recalls the preparatory procedure in designing new mixtures. The grade of asphalt, whether it is viscosity or penetration graded should be specified first. The same procedure is required in designing recycling mixtures.

- 2) Establishing blending curves with the extracted asphalt from the highway and several possible softening agents is strongly recommended. By doing this, the necessary concentration of each agent to obtain the target viscosity of the blend can be available. As the agent, various types of asphalt cements, emulsions, and commercially available agents are possible.
- 3) A stability test should be performed for possible combinations of the blends and the void ratio analysis should follow. It is recommended two or three levels of the amount of the agent be tried within the allowable range of the target viscosity.
- 4) When the asphalt is heavily oxidized and it is suspected that the initial softening effect may take place, a stability test or preferably the creep test should be performed continually for a few weeks to ensure that stability requirements are being met.
- 5) Gradation control of the old mixtures should be performed as much as possible to secure an even dispersion of the softening agent.

12-4 Conclusions

From the results of this study, the following conclusions are presented. Although they are thought to be appropriate over a wide range of application, it must be

borne in mind that these conclusions are known to be valid only for the materials and methods used in this study.

- 1) Recycling by a cold process using emulsified asphalts or commercially available rejuvenating agents is possible. When the old mixtures to be recycled contain mildly weathered asphalt, recycling may produce even a surface course material. When the asphalt of the old mixtures is strongly oxidized, the resultant mixture may be used as a base course material, but instability in the mixture may take place when the difference in viscosities between the agent and the old asphalt is comparatively large and the dispersing ability of the agent is weak.
- 2) A soft grade of asphalt cement can reduce the viscosity of old asphalt cement, but its effectiveness as a recycling agent is open to question.
- 3) With respect to the long-term properties of cold recycled mixtures, the viscosity of the blend of the old asphalt and the agent changes with time and therefore affects the properties of the mixtures as the age progresses.
- 4) The creep test utilizing viscoelastic principles can be used to measure the long-term behavior of cold recycled mixtures.
- 5) An accelerated weathering procedure utilizing elevated temperature affects specimens in a different way than

that produced by non-accelerated weathering utilizing ambient conditions.

RECOMMENDATIONS FOR FURTHER RESEARCH

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

1. This study was limited to only one type of the original material in which only one gradation of aggregate, one type of asphalt and two levels of oxidation were used. The laboratory investigation should be extended to include other types of mixtures to obtain a more general conclusion.
2. The creep behavior was observed at only one temperature level. By estimation it should be possible to understand the high and low temperature properties of the recycled mixtures. Nevertheless, observing the creep behavior at different temperatures is recommended to introduce more accurate design guidelines.
3. Certain relationships were found in the blending curve between the consistency of the blend and the concentration of the softening agents. To make sure of the relationships, other asphalt cements should be tried as the base asphalt. Physico-chemical analysis may be required to establish the general behavior of the blending curve.

4. The property of AE-150 and other emulsified agents that raise the value of η_3 is a very important property to the performance of an asphalt mixture because the permanent deformation of the mixture due to traffic loads will be reduced by high value of η_3 . The cause of this property may be worthwhile to analyze.
5. Viscoelastic interpretation of asphalt mixtures using the creep test results was shown to be possible. This method might be used to interpret other unknown mechanical properties such as the Marshall stability. Further research is recommended in viscoelastic interpretation.

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NOTICE

The two appendices for this report are not included in this copy of this report. They are titled as follows:

Appendix A - List of Computer Programs to Compute
the Creep Parameters

Appendix B - List of Creep Parameters

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

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