FINAL REPORT

TRANSPORTATION RESEARCH PROJECT NO. 65

EVALUATION OF ASPHALT EMULSION SURFACE TREATMENT CHARACTERISTICS AND PERFORMANCE

Conducted For
The Arkansas State Highway and Transportation Department
in cooperation with
The U.S. Department of Transportation
Federal Highway Administration

by

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16. Abstract

A methodology for evaluating the characteristics and performance of asphalt emulsion seal coats in the laboratory has been developed. A relationship between the aggregate spread modulus and the ratio of aggregate and asphalt application rates to obtain optimum performance was developed. The results of the 20 month long investigation were based on sampling and testing of the in-place seal coat and its emulsion residue and aggregate components. The samples were obtained from 17 seal coat projects constructed by the Arkansas State Highway and Transportation Department District maintenance sealing crews during the 1981 construction season. All of the seal coat projects were constructed using a CRS-2 asphalt emulsion. The mineral aggregate used in the seal coats represented the various types and sizes of aggregates available for seal coat construction in Arkansas. Physical properties of the in-place seal coat, mineral aggregate, CRS-2 emulsion residue and parent asphalt cement were correlated to obtain their most significant relationships. The performance of each seal coat project was determined by use of an accelerated wear device. This device included a 28 inch diameter circular wear track, where the seal coat samples were subjected to 30,000 passes of the rubber tires of the apparatus. The seal coat projects constructed using the class 7 (minus 3/4") or class 8 (minus 1/2") chips provided a more durable pavement surface than did the seal coat projects constructed using the finer graded crushed gravel material. Better embedment of aggregate was obtained on the seal coat projects where steel wheel rollers were used in conjunction with pneumatic tire rollers.

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ADDENDUM

The following are comments made by the Arkansas Highway and Transportation Department on the contents and recommendations of TRC-65 "Evaluation of Asphalt Emulsion Surface Treatment Characteristics and Performance":

1. The AHTD Specification Committee is considering the inclusion of pertinent recommendations in the new Standard Specifications.

2. For clarification to the report, the extracted aggregate sieve analysis reported in Chapter 5 reflects only the aggregate particles which were attached to the asphalt binder on the sample plate. The size of sample from the sample plate is too small to be representative of the aggregate stockpile. All AHTD stockpile samples taken prior to construction met the required gradation limits. The sieve analyses on the aggregate extracted from the sample plates and the AHTD stockpile samples are shown in Table VIII.

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The opinions, findings, and conclusions expressed in this publication are those of the author and not necessarily those of the Arkansas State Highway and Transportation Department or the Federal Highway Administration

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ABSTRACT

A methodology for evaluating the characteristics and performance of asphalt emulsion seal coats in the laboratory has been developed. A relationship between the aggregate average particle size, the ratio of aggregate and asphalt application rates and the aggregate coverage to obtain optimum performance was developed. The results of the 20 month investigation were based on sampling and test of the in-place seal coat and its emulsion and aggregate components. The samples were obtained from 17 seal coat projects constructed by the Arkansas State Highway and Transportation Department District maintenance sealing crews during the 1981 construction season. All of the seal coat projects investigated were constructed using CRS-2 asphalt emulsion. The mineral aggregate used in the seal coats represented the various types and sizes of aggregates available for seal construction in Arkansas.

The samples of asphalt emulsion and their parent asphalt cement represented all six of the asphalt emulsions plants in Arkansas. Out of state emulsion suppliers provided CRS-2 emulsion for two of the seventeen seal coat projects investigated. Physical properties of the in-place seal coat, mineral aggregate, CRS-2 emulsion residue and parent asphalt cement were correlated by regression analysis to obtain their most significant relationships. The physical characteristics of the CRS-2 residual asphalt from the distillation test were about the same as the parent asphalt cement, except for being somewhat harder. The viscosity of the residual asphalt was about 20 percent higher than the viscosity of the base asphalt cement.

The performance or relative durability of each seal coat project sample was determined by use of an accelerated wear device. This device

was a 28 inch diameter circular wear track, where the seal coat samples were subjected to 30,000 passes of the rubber tires of the apparatus. The seal coat projects constructed using Class 7 (minus 3/4") or Class 8 (minus 1/2") crushed stone and pea gravel aggregate provided a more durable pavement surface than did the seal coat projects constructed using the crushed materials sized to meet the grading limits of a Special Mineral Aggregate (minus 3/8"). Seal coat samples taken from projects constructed using pneumatic and steel wheel rollers indicated greater durability than samples taken from projects using only penumatic rollers.

GAINS, FINDINGS, AND CONCLUSIONS

A method of evaluating the performance of surface treatments in the laboratory has been developed. The aggregate average particle size and the ratio of aggregate application rate to obtain optimum performance was developed. New types of binders and aggregates may be evaluated to determine their capability for use as surface treatment materials. The seal coat pavements constructed using Class 7 (minus 3/4") or Class 8 (minus 1/2") crushed stone or pea gravel aggregate provided a more durable laboratory sample than did the seal coat pavements constructed using the finer crushed material (minus 3/8") sized to meet the grading of a Special Mineral Aggregate. There was a very good correlation between the absolute viscosity of the parent base asphalt cement and the CRS-2 residual asphalt. There was a hardening effect indicated on the asphalt cement after it was used in the manufacture of the CRS-2 asphalt emulsion. The seal coat pavements constructed with a harder residual asphalt had a higher retention of their surface aggregate in the Accelerated Wear Device test than did seal coats constructed with a softer residual asphalt. Better embedment of aggregate was obtained on the seal coat samples where steel wheel rollers were used in conjunction with pneumatic tire rollers. There was no significant relationship between the CRS-2 emulsion Saybolt viscosity test results and other measured properties of the CRS-2 emulsion, base asphalt cement, and the seal coat physical properties.

IMPLEMENTATION STATEMENT

The results of this research work may be used to design longer lasting and more economical seal coat pavements using the methodology presented in evaluating the proper application rate of asphalt and aggregate in relation to the aggregate character and gradation. It is recommended that specifications for aggregate grading limits for Class 7 (minus 3/4") and Class 8 (minus 1/2") materials be revised to include the 3/8 inch sieve for the Class 7 materials (limits of 18 to 45 percent retained); and to include the No. 4 sieve size for Class 8 materials (limits of 60 to 80 percent retained). This action would provide a more consistent aggregate material that may facilitate uniform aggregate application rates.

The correlation of actual seal coat performance with their predicted service life as indicated in Figure 46 of this report would provide insight into the relative merits of each seal coat project investigated. It is therefore recommended that a continued effort be made to monitor the 17 seal coat projects investigated in this research work until they are resurfaced. After differential traffic and environmental effects are considered, a better method of seal coat design would be confirmed.

Steps should be taken in construction to insure the initial embedment of the mineral aggregates into liquid asphalt. This embedment was accomplished by the AHTD sealing crews by coordinating the speed of the distributor truck, chip spreader and rollers. The aggregate that was placed and rolled as soon as possible after the application of the emulsion provided the more durable seal coat samples. The use of pneumatic wheel rollers and steel wheel rollers with as high a contact pressure as the aggregate can withstand without crushing would contribute greatly to obtaining a good seal coat.

An evaluation of Special Mineral Aggregate (minus 3/8") for use in seal coats as to their true economy in view of their poorer durability than the seal coat samples constructed with Class 7 or Class 8 materials is warranted. The Class 7 or Class 8 aggregates used on the seal coat study samples indicated double the resistance to wear of a Special Mineral Aggregate seal coat.

ACKNOWLEDGEMENTS

The author expresses his thanks to members of project committee, Norman D. Pumphrey, Bob Hickey, L. L. Hodnett and Jim Tucker for their guidance and assistance in the accomplishment of this research. The continued assistance and support of the project coordinators, Alan Meadors and Jon Annable is deeply appreciated. Acknowledgement is also given to E. John Baker, Jr. who assisted in carrying out this work, and to the many Civil Engineering undergraduate students who performed the laboratory work.

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CHAPTER 1

INTRODUCTION

This investigation was initiated in August 1980 with the purpose of evaluating the characteristics and performance of asphalt emulsion surface treatments. Surface treatments are useful in waterproofing bases and old pavements that have weathered and show signs of cracking. They also may be used to provide a skid resistant surface for pavements that have become slippery because of wear and polishing of surface aggregate. A seal coat is a surface treatment that consists of a single application of asphalt to the road surface followed by a single layer of aggregate of a uniform size as possible. The layer of asphalt is deposited as a liquid and coats the road surface and serves as a binder to hold the cover aggregate to the road surface after the liquefying agent evaporates.

In years prior to 1973, most seal coats in Arkansas employed cutback asphalts. A cutback asphalt is made from asphalt cement and a petroleum solvent. Since 1973, along with the energy crisis and air pollution standards, the use of asphalt emulsions for seal coats has been encouraged by Federal Highway Administration (FHWA) Notices and Environmental Protection Agency (EPA) rules and regulations.

In general, the seal coats made with emulsions do not seem to perform as well as the earlier seal coats. Problems have developed in consistently obtaining a satisfactory seal coat using emulsified asphalts. The viscosity of the emulsion tends to fluctuate during transportation and use. Sometimes the emulsion will coat the pavement and retain the cover aggregate, while other distributor loads from the same tank truck will not stick. An increase in stripping and raveling of emulsion seal coats has been observed. Due to their experience with this poorer performance of asphalt emulsion seals, highway engineers may tend to use overlays of asphalt concrete hot-mix (ACHM) to take care of pavement maintenance that would only have required a seal coat in the past. The use of ACHM overlays is not economical for low and medium traffic roads. There is an urgent need to understand why the asphalt emulsion seal coats are not as consistently reliable as previously used materials.

In the United States over 1,700,000 miles of state, county and municipal roads and streets have either a seal coat or surface treatment applied to them, according to the FHWA Highway Statistics (1)[1]. In Arkansas alone, over 5300 miles of the state highway system have a bituminous surface (2). With the continued rise in materials and construction costs, it is important that seal construction materials be utilized to their optimum capability. Properly designed and constructed seal coats have been used in many areas for 10 to 14 years before having to be resealed.

Initially this research project was designed to: identify the physical and chemical characteristics of the asphalt emulsions used in Arkansas seal coats; relate the performance of seal coats to these properties; and evaluate alternative bituminous materials or additives that may be used to improve seal coat performance. Due to a limit on funds available and time allowed for completion, only the characteristics of the asphalt emulsions, base asphalt cements, and aggregates have been evaluated and related to their performance when combined into seal coats.

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[1] The number in parenthesis corresponds to the listing of the literature cited in the Reference section.

Asphalt emulsions are dispersions of very small droplets of asphalt cement in water. Since asphalt and water are immiscible liquids, emulsifying agents are required to facilitate dispersion of the asphalt in the water and to maintain this dispersion. Cationic rapid setting emulsions (CRS-2) are generally used in Arkansas seal coat construction. The surfaces of the asphalt droplets in these emulsions carry positive charges, and the emulsifying solution is acidic. Certain fatty diamine salts and quaternary ammonium salts are used as emulsifying agents. These materials must also be compatible with both the asphalt cement and the water. Due to the positive surface charge on the droplets, CRS emulsions adhere best to acidic (hydrophilic) or electro-negative aggregates. In general, the cationic emulsions exhibit a more rapid initial set or "break" than do the anionic emulsions because of the strong preferential attraction of the cationic agent.

Cationic emulsions are designed to break upon contact with a foreign substance such as aggregate or a pavement surface. The rate of breaking is controlled by the type and concentration of the emulsifying agent, along with atmospheric conditions. In general, these factors affect the curing rate of an emulsion: the rate of water absorption of the aggregate; weather conditions; mineral composition and surface area of the aggregate; and mechanical forces brought to bear by rolling and traffic.

There has been only a limited amount of research performed on asphalt emulsion seal coats. Presently, design methods are based on previous experience with cutback asphalts. This study on the characteristics of cationic asphalt emulsion seal coats is desirable since there are unanswered questions associated with obtaining good field performance.

The approach to solving the problem of asphalt emulsion seal coat performance is to evaluate the adhesion and durability characteristics of asphalt emulsions used in Arkansas in relationship to the mineral aggregate, construction practices and environmental factors. The approach used to determine the characteristis of CRS-2 seal coats is to obtain samples of the materials involved, along with actual samples of newly constructed seal coats and evaluate their physical properties. Effects of traffic on the seal coat were determined by installing the seal coat samples on a circular wear track and measuring the amount of material detached by the rubber tires of the test apparatus. The asphalt emulsion and its base asphalt cement were tested to determine their characteristics. The aggregate's abrasion pH value and other physical properties were evaluated.

Samples of asphalt emulsion, mineral aggregate and inplace seal coats were obtained from 17 different construction projects at the time of their construction. The CRS-2 asphalt emulsion was produced at eight different plants of five different manufacturers; all six emulsion plants in Arkansas were included in the sampling process. The seal coat samples were taken from projects being constructed by the Arkansas State Highway and Transportation Department maintenance sealing crews. At least one seal coat sample was taken from each of the ten different highway district sealing crews. Samples of 14 base asphalts used in manufacturing the 17 emulsions were obtained. The aggregates that were used in these seal coat projects represent the various aggregates available for seal coat construction in Arkansas. Six of the aggregates were crushed limestone or sandstone, six were pea gravel, five aggregates were crushed gravel and one aggregate was creek gravel. The aggregates ranged in size from class 7 (minus 3/4 inch) to special mineral aggregate (minus 3/8 inch).

A total of 102 samples of actual seal coats were taken. The seal coats were constructed between June 15, 1981 and August 12, 1981. These samples were tested on the accelerated wear track to determine their relative durability. Physical test properties of the emulsion, base asphalt aggregate and seal coat were correlated with the durability or performance of the seal coats as evaluated by the wear track test.

A field condition rating for each of the 17 seal coat projects (as of March 1982) is reported. The results of these laboratory and field investigations will be useful in selecting the optimum application rate for asphalt and aggregate material and the more desirable aggregate to use in constructing better, longer lasting seal coats. When over a period of years, field condition performance evaluations are correlated with the laboratory durability of results of this study, a better method of seal coat design may be confirmed.

CHAPTER II

LITERATURE REVIEW

A seal coat is a thin layer of aggregate and bituminous material, applied over an existing bituminous surface, which is directly subjected to the forces of vehicular traffic and in which the aggregate is bound to the underlying surface by being partially embedded in the film of bituminous material. Even though the terms "seal coat" and "surface treatment" are sometimes used interchangeably, a surface treatment is usually applied over a base course of some specified material, sometimes in multiple applications, while a seal coat is applied over an existing bituminous surface in one application.

Asphalt emulsion seal coats are primarily used for low to medium traffic volume highways. The seal coat consists of an application of asphalt emulsion to the previously prepared base or existing pavement, followed by an application of cover aggregate. The aggregate is seated in the asphalt emulsion by rolling. Factors which affect the performance of the seal coat include: application rates, emulsion characteristics, aggregate characteristics, construction techniques, environment, and traffic.

Historical Perspectives

The predecessor to today's asphalt emulsions was patented in the United State in 1869. It consisted of resins, tar residues, and waste rubber emulsified with a silicate of soda (3). The first use of an asphalt emulsion in highway work was in 1905 when the City of New York began using an asphalt emulsion to control the dust problem and surface erosion brought on by the use of the automobile. By 1914 the New York State Highway Department was extensively using emulsions for cold patching of existing pavements.

After World War I, a vast system of waterbound macadam pavements in France, Germany and England was extremely worn and in a state of disrepair. Money was scarce and an economical quick-setting emulsion was developed that could be applied to the surface of the macadam pavements and then covered by a layer of crushed stone. This was the first use of an asphalt emulsion for seal coat work. The first use of an asphalt emulsion for seal coat work in the United States occurred in 1927 when a ten mile stretch of country road in Miles Canyon, Alemeda, California, was sealed. The road was used as a detour while major construction of a state highway occurred nearby. The country road handled over 1,000 vehicles per day for ten years before having to be resealed (5).

Anionic asphalt emulsions had gained wide acceptance in the United States by 1935. France developed the first cationic emulsion in 1936 and it has been the principle type of emulsion used in Europe since 1951. The cationic asphalt emulsion was introduced in the United States in 1957 but was confined to the rapid-setting type used primarily in seal coat construction.

In December 1971, the Federal Highway Administration (FHWA) issued a notice dealing with the conservation of fuel in highway construction programs involving federal funds. Another notice was issued in January 1974, directly concerning itself with the use of emulsified asphalts in lieu of cutback asphalts. The notice pointed out that, based on the total quantity of cutback used in the United States in 1972, 309 million gallons or 1.28 million tons of petroleum products in critical supply could have been saved if emulsified asphalts had been used in place of the cutbacks. The FHWA notices encouraged the use of asphalt emulsions in seal coat work (7).

Asphalt Emulsions

An asphalt emulsion is an intimate mixture of very fine asphalt droplets dispersed in water by mechanical means. A third component of an emulsion, called an emulsifying agent, promotes emulsification and keeps the emulsion stable after formation. The physical and chemical properties of the emulsion are largely dependent on the chemical type and molecular structure of the emulsifying agent.

Classification

Asphalt emulsions are classified by the particle charge on the dispersed asphalt phase and their rate of setting. The term anionic describes emulsions in which the disperse phase has a negative charge and would therefore be attracted to a positively charged anode or surface. Conversely, positively charged asphalt particles will move to the cathode, or negatively charged surface, and the emulsion is known as cationic. Nonionic emulsions carry a neutral charge and are not used to any great extent in highway work at the present time. A cationic emulsion is denoted by a "C" in front of the emulsion type. The absence of the "C" denotes an anionic emulsion (8).

Emulsions are further classified on the basis of how quickly the asphalt will coalesce, or revert back to, an asphalt cement. The terms RS, MS, and SS are used to classify rapid-setting, medium-setting, and slow-setting emulsions. The terms are relative and the setting times are greatly influenced by the types of emulsifying agents used in the manufacture of the emulsion (8).

Components of an Asphalt Emulsion

Asphalt cement is the basic component of an asphalt emulsion and in most cases makes up from 55 to 70 percent of the emulsion. Emulsions with a high asphalt content have better all around properties both in laboratory test and field performance (4). Hardness of the base asphalt may be varied as climatic conditions dictate but most asphalts used in emulsions are in the 100-250 penetration range. The particle size of the dispersed asphalt was found to be more directly related to the rate of curing and stability than any other property. Some authorities believe that the resulting particle size of the asphalt is considerably dependent on the pH value of the system (3).

Water is the second largest component of an asphalt emulsion. It controls the chemical reactions and is the primary source of the wetting ability of an emulsion. Dissolved mineral ions such as calcium and magnesium can affect the properties of an anionic emulsion. Water containing foreign matter results in the unbalance of the emulsion components which may adversely affect performance or cause premature breaking (4).

The properties of an asphalt emulsion depend greatly on the chemical used as the emulsifying agent. The emulsifier is a surface-active agent commonly called a surfactant (9). Such molecules will show positive adsorption at a liquid interface. The pH value or the acidity or alkalinity of an emulsion is not related to the charge on the particle but is determined by the type of emulsifying agent used. Ideally, emulsifiers should have no adverse effects on asphalt properties. Emulsifier concentrations used in asphalt emulsions range from 0.3 to 6.0 percent of the asphalt content (6).

The most common anionic emulsifying agents used today are fatty acids which are wood-product derivatives such as resins and lignins. Anionic emulsifiers are saponified, or turned into soap, by reacting them with sodium or potassium hydroxides. Particle size is affected by the concentration and type of hydroxide used. Asphalts from different sources differ in the range of pH at which optimum particle size can be obtained (3).

Cationic emulsifiers are fatty amines or fatty quarternary ammonium salts. The amines are converted into a soap by the addition of hydrochloric or acetic acid. The ammonium salts are water soluble and do not require the addition of an acid. A distinct advantage that cationic emulsions have over anionic emulsions is that they can be prepared with hard water, that is water containing considerable amounts of magnesium and calcium ions (6).

A high float emulsified asphalt contains oil or a lighter petroleum fraction in the emulsion. These emulsions contain from one-half percent to six percent oil by volume. The advantages of using a small portion of oil include improved wetting properties of the liquid emulsion, control of the penetration range of the residual asphalt, and the oil allows the asphalt to exhibit non-Newtonian flow. The oil portion of the emulsion also promotes a slower setting rate (10).

Properties of an Asphalt Emulsion

Emulsions are fluid at room temperature and the viscosity remains almost the same over the normal range of atmospheric temperature changes. Emulsion viscosity should remain constant on contact with the road or aggregate surface. A good quality emulsion will exhibit viscosity stability during storage and handling (4).

Viscosity increases slowly with asphalt content up to appoximately 65 percent asphalt by weight of total emulsion and rapidly thereafter. Emulsions of high viscosity are used when relatively thick films of asphalt are needed. Emulsions of low viscosity are used when small aggregate particles must be evenly coated. The effect of asphalt content on emulsion viscosity for a typical asphalt emulsion is shown in Figure 1 (4).

Settlement refers to the change in concentration of the disperse phase in different levels of the emulsion stored in containers. Emulsions generally follow Stoke's law. Settling of coarser particles (5 to 10 microns) in emulsions is termed sedimentation. This may occur with no indication of a break or rupture of the emulsion.

Creaming is the opposite of settlement and occurs when the asphalt of the dispersed phase has a density less than the water phase. The asphalt emulsions have very little tendency toward concentration of the disperse phase when stored for a reasonable length of time (4).

Demulsibility is a measure of an emulsion's ability to release its disperse phase when it comes in contact with a bivalent ion. Certain chemicals such as calcium chloride will cause premature breaking if they are allowed to come in contact with the emulsion.

Theory of Asphalt Emulsification

Mertens and Wright (11) wrote some of the first authoritative material on the processes involved in the emulsification of asphalt

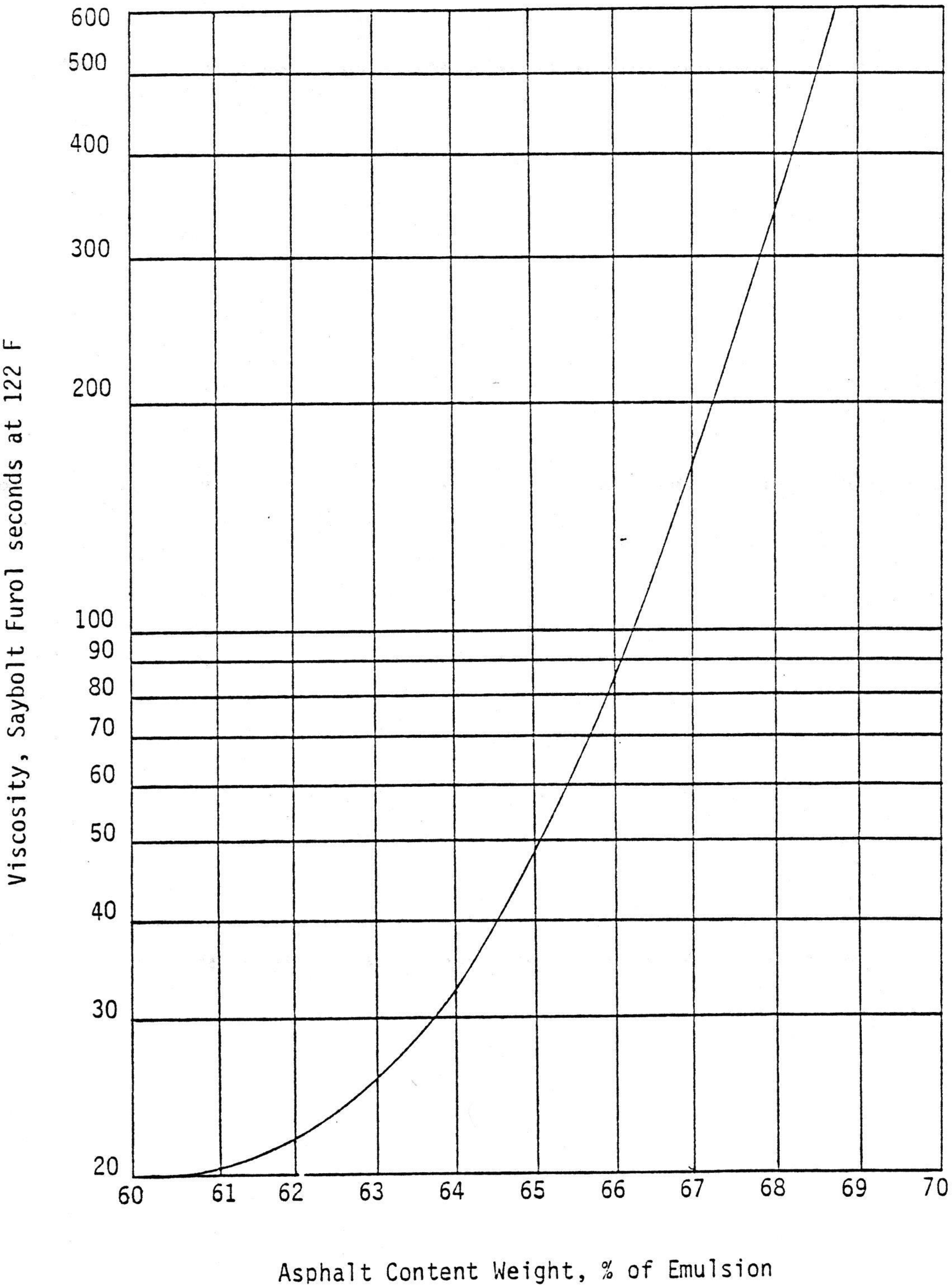


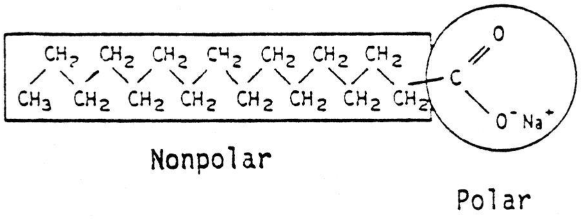
Figure 1. The Effect of Asphalt Content on Emulsion Viscosity for a Typical Asphalt Emulsion (**4**)

cement. They explained why the physical and chemical properties of the emulsion are largely dependent on the chemical type and molecular structure of the emulsifying agent. The emulsifier promotes emulsification, reduces the interfacial tension between the asphalt and the water and keeps the asphalt stable after formation.

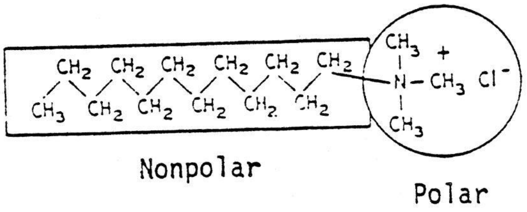
The fact that the emulsifying agent must be compatible with both the asphalt and water phases in an emulsion system requires the emulsifying molecules to be of the mixed nonpolar-polar type. Figure 2 shows an anionic and cationic emulsifying agent and their respective polar and nonpolar parts. The polar heads of the molecules orient in the water phase while the hydrocarbon tails project into the asphalt phase. The film formed by this molecular orientation is called the interfacial film. Researchers have disagreed on whether the film is one or more than one molecule thick.

When the emulsifying agent is added to the water, the molecule migrates to the surface and orients itself at the air-water interface or shields itself from the water by aggregating as shown in Figure 3. A cluster of molecules in which the hydrocarbon tails are shielded from the polar heads is called a micelle. Such a phenomenon will not occur unless the molecules are present in sufficient quantities. The concentration of molecules required for the formation of micelles is called the critical micelle concentration.

Once the critical micelle concentration of an emulsifying agent is reached, the molecules can dissolve their hydrocarbon tails into nonpolar asphalt surface. This process is called solubilization and the micelles become swollen in the process. The end result of the solubilization mechanism is shown in Figure 4, where the micelles have attached themselves to the asphalt.



Anionic Emulsifying Agent



Cationic Emulsifying Agent

Figure 2. Typical Anionic and Cationic Emulsifying Agents and Their Respective Polar and Nonpolar Parts (11)

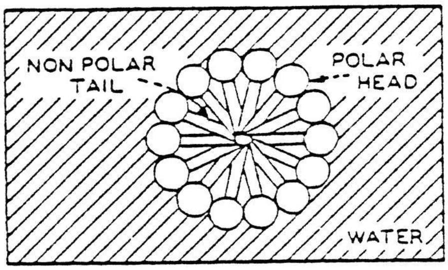


Figure 3. Soap Micelle (11)

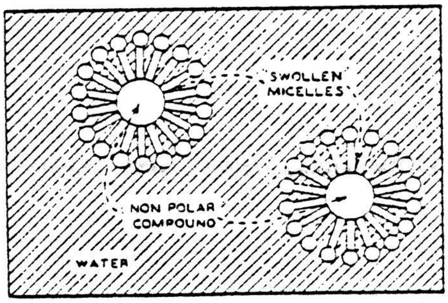


Figure 4. Solubilization (11)

Many asphalts contain enough acid components (asphaltogenic acids) to produce fine dispersions of asphalt in water when the liquid asphalt is run through a colloid mill with a dilute alkaline solution. A soap-like emulsifying agent is produced in situ. Those asphalts containing no acids are classified as nonemulsifiable and will not emulsify when mixed in an alkaline solution unless suitable acids are added prior to emulsification.

All asphalts used in cationic emulsions are considered nonemulsifiable and the cationic emulsifying agent must be added to the system. High molecular weight amines or ammonium salts are added to a dilute solution of a water soluble acid prior to emulsification. The amount of acid contained in the water is in excess of that needed to neutralize the amine, therefore the emulsion is acidic. The concentration of the acid is critical. If the pH of the emulsion is relatively high, better adhesion will result. However, emulsion stability is favored by a low pH (6). The asphalt particle absorbing the emulsifier is shown in Figure 5, with the chlorine ion being released. Figure 6 shows the resulting cationic emulsion droplet and the suspension with its various ions.

Emulsifiers should have no adverse effects on the base asphalt properties but materials used in large concentrations will exert both beneficial and detrimental effects on the asphalt. Montmorillonite clay used in some anionic emulsions will increase the asphalt viscosity. Silicones, even when added to emulsions in very small quantities to prevent foaming, will alter the penetration of the base asphalt. Cationic emulsifiers have less effect on the penetration, softening point and viscosity of a recovered asphalt than do anionic emulsifiers (6). It must be remembered that the emulsifier remains in the asphalt even after

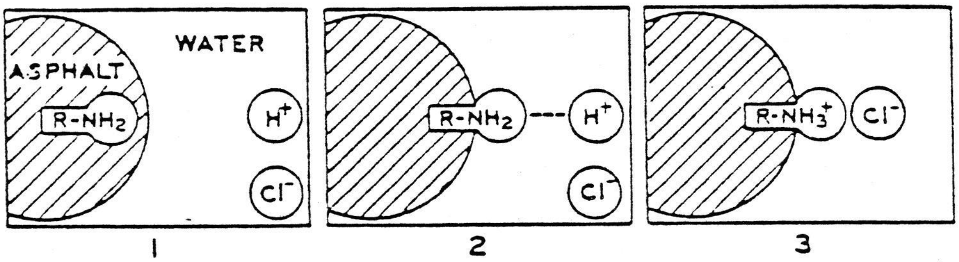


Figure 5. In Situ Emulsification of a Cationic Emulsion (11)

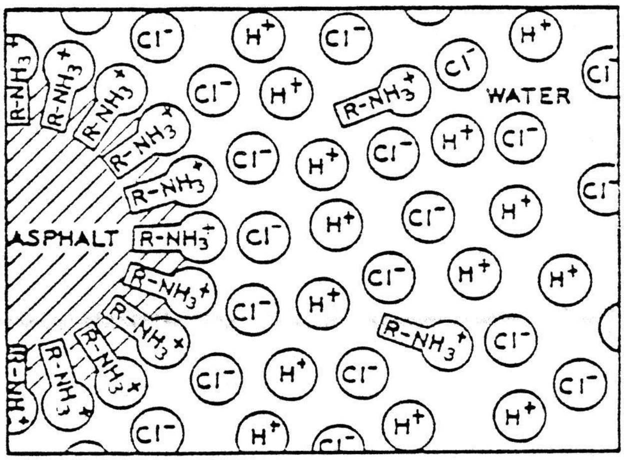


Figure 6. Cationic Emulsion Asphalt Droplet (11)

the water has left the system (3). Neither cationic or anionic emulsifiers had any significant effect on the oxidation resistance of the asphalt.

Breaking and Curing of Asphalt Emulsions

If the asphalt emulsion is to perform its function, the asphalt must separate from the water phase. The rate at which the asphalt separates from the water is called breaking or setting. The rate of breaking is controlled primarily by the specific type and concentration of the emulsifying agent, but is also influenced by the pH of the emulsion, surface area of the aggregate, atmospheric conditions and the type of mineral which is applied to it.

The breakdown of an emulsion is considered a complex phenomenon. During the breakdown of an emulsion an adsorption phenomenon, presumably related to Van der Waals forces, predominates. An exchange of ions between the emulsifying agent and the aggregate takes place. For limestone aggregate the exchange capacity is considerably higher than for siliceous ones due to a higher charge on the ions. The pH of the emulsion is very important for the mechanism of adsorption since it would condition the type of adsorbed molecule (5).

For seal coat uses, both anionic and cationic asphalt emulsions depend on the evaporation of water for development of their curing and adhesion characteristics. Water displacement can be fairly rapid under favorable weather conditions but high humidity, low temperatures or rainfall soon after application can deter proper curing. Bohn (12) has studied the breaking and curing rates of emulsions and has determined that the wind velocity and the humidity of the air is of decisive importance. When the water evaporation velocities increase, the emulsion setting times are strongly reduced. It has been found that cationic emulsions tend to give up their water a little faster than anionic emulsions.

Pinella and Agnusdei (13) have studied the effects that mineral type, temperature and emulsifier concentration have on the setting rate of emulsions. They have also found that the greater the specific surface area of the aggregate, the faster the rate of setting of the emulsion. The time of breakdown decreases with an increase in temperature and with the type of aggregate used.

Other factors which influence the setting rate of an emulsion include:

1. The rate that water is absorbed by the aggregate. A rough-textured, porous aggregate speeds the setting time of absorbing water from the emulsion.
2. Moisture content of the aggregate prior to mixing.
3. Mechanical forces brought to bear by rolling and by traffic. Roller pressure, to a limited extent, forces the water from the materials.
4. Size distribution and mineral composition of the aggregate. Seal coats with fine aggregate tend to break faster because they possess greater surface area than an equal weight of coarse aggregate. The mineral composition also affects the speed at which the asphalt emulsion breaks. There may be some type of chemical reaction between the emulsifier and the aggregate surface. Also, dirty aggregate or excessive fines may accelerate breaking and retard curing.

5. Intensity of charge on the aggregate versus intensity of emulsifier charge, in combination with surface area, is a major setting-rate determinant.

Mineral Aggregate

The characteristics of an aggregate are widely accepted as one of the most important factors that affect adhesion and aggregate retention in a seal coat. Aggregates have been defined as being hydrophilic or hydrophobic. Silica, quartz and gravel are examples of hydrophilic aggregates whereas limestones are considered hydrophobic.

Classification of Aggregates

Mertins and Wright (11) point out that the terminology in classifying aggregates as either hydrophilic or hydrophobic is incorrect for the term "hydrophobic aggregate" implies that it cannot be readily wetted by water. Actually, limestones are as readily wetted by water as the hydrophilic aggregates. Mertens and Wright suggest that these two types of aggregates be classified as electropositive and electronegative when describing limestones and siliceous types of aggregate. It is commonly accepted that the electrochemical property of an aggregate surface must be compatible with the emulsion in order to obtain good adhesion. This property may be the surface charge the aggregate possesses when it is in contact with water.

Rarely is an aggregate found that is totally electropositive or electronegative. Most aggregates contain elements which cause both types of electrical properties to exist on the surface of the aggregate to varying degrees.

Particle Size

The primary purpose of the aggregate layer is to provide projecting mineral particles. Normally the effectiveness of the seal coat is determined by the mineral surface supplied. Particles which are so small as to be submerged by the binder serve no practical purpose and large particles which are inadequately held are subject to dislodgement.

Predominantly coarse aggregates provide too few points of contact; likewise the wear is concentrated on these few projections which are worn down very quickly. It has been found that the 1/4" to No. 10 fraction exerts a considerable blotting action on the asphalt film. Nevitt (14) found that aggregates below the No. 10 and above the 1/2" screen seem undesirable. He states that stone particles between the 1/4" to 3/8" screens are best. The use of clean aggregate, free from dust or fines, and the use of less than 2 percent passing the No. 200 sieve is highly recommended even though the use of fines, including minus No. 10 material, does not produce undesirable effects when emulsions are used (15).

In much of the literature written on seal coat aggregate a majority of authors have suggested that the cover should be as nearly one-size as is possible to obtain. McLeod (16) defines one-size aggregates for seal coating purposes as those aggregates that have a gradation of 60 to 70 pecent by weight of the aggregate passing the specified sieve and retained on a sieve having an opening that is seven-tenths of the specified size. If an appreciable variation of aggregate size exists the smaller particles are completely submerged, while the larger sizes are inadequately held. Benson (17) has suggested a maximum to minimum size ratio of the largest stone particle to the smallest stone particle in an aggregate mix of two to one. Nevitt (14) suggests a ratio of 1.0 to 1.5 or 2.0. The use of a small size stone is more resistant to degradation than the larger stones of the same type and quality, but as the aggregate size is decreased, the possibility of applying too much binder and filling the voids is increased. This possibility can result from construction procedures or the improper use of equipment. The result is flushing or bleeding of the surface.

Nevitt (14) has made a distinction in the principal and critical sizes of aggregate particles used in seal coat work. He defines the principal size as the screen opening corresponding to the 50 percent point when the screen analysis is plotted against the total percent passing or retained on each screen. The aggregate dealt with is essentially one-sized and lies within a narrow range on the grain size curve. The critical size is a particle size which will permit the tire tread rubber just to touch the binder yet not transmit any load to it. This is important in that it prevents the tire from picking up the asphalt, reducing the binder content and possibly its aggregate retention properties, and blackening the surface.

There are two objections to particles with their controlling dimensions below some predetermined ratio to the principle size. One is that they hinder the adhesion of the larger particles of the desired size; the other is that they are functionally ineffective and, therefore, not economical. The finer particles tend to blot or form a covering over the binder so that the larger stone particles are not immersed immediately and sufficient embedment into the binder to retain the aggregate will not occur. The residual aggregate has an unbalanced gradation and the aggregate application rate is no longer correct for the aggregate layer achieved. It is estimated that particles which do not project more than 20 percent of their height above the binder have little or no functional value (14).

The objections to a large particle size do not apply to scattered large particles provided that they do not stick out of the seal coat enough to cause tire injuries. The scattered large particles will get the full impact of traffic yet their relative embedment is small since they project far above the bitumen and are, therefore, subject to dislodgement. The adhesion provided by the residual asphalt is the primary source of the aggregates' resistance to dislodgement.

Many methods are used to find the principal or average particle size that is used to determine the aggregate application rate. One method is obtaining the size at a predetermined percentage on the aggregate gradation chart. Another method is by establishing the average least dimension. The average least dimension was found to be determined by two methods in the literature--the weighted average of the sieve size opening times the percentage passing or retained on the individual sieves and the mean size versus the flakiness method. The mean aggregate size is plotted against the flakiness index to obtain the average least dimension. The average least dimension is used in the McLeod (16) method of seal coat design. The flakiness index of an aggregate is the percentage by weight of particles in it whose least dimension is less than three-fifths of their mean dimension. The companion to the flakiness index is the elongation index: the percentage by weight of particles whose greatest dimension is greater than one-and-four-fifths times their mean dimension. Both indices are based on test procedures of British Standard 812.

Quantity

The quantity of aggregate needed is the amount which is required to form a layer of one stone depth in which there is preferably an interlocking of the particles. It is important that the least average dimension of the aggregate is facing in an upward direction when the aggregate quantities are determined since the forces exerted by rolling and moving vehicles will rotate the aggregate particles until they have reached their position of maximum stability. This position of maximum stability is with the long, flat side of the stone facing down.

The position of cover aggregate particles immediately after application are shown in Figure 7 (16). After considerable traffic the cover aggregate is oriented as shown in Figure 8. The least average dimension of the particles is also indicated in Figure 8. In their final position the correct quantity of aggregate needed depends on the size, shape, percent of voids, and loose unit weight of the aggregate. The percentage of voids in the loose unit weight is about 50 percent for most aggregates. The final compacted percentage of voids is about 20 percent. The 20 percent voids applies to all aggregate regardless of its nominal size (16). The percent voids must be calculated since it is the basis on which the amount of asphalt to fill a certain percentage of the voids is determined. Many design equations assume that from 10 to 20 percent of the total surface area, after the aggregate has been applied and the aggregates have reoriented themselves, are voids.

The amount of aggregate applied to the surface is actually greater than the amount that will eventually stick to the binder to achieve a mat one stone particle thick. This increase is due to inaccuracies in spreading and aggregate whip-off. The recommended magnitude of the

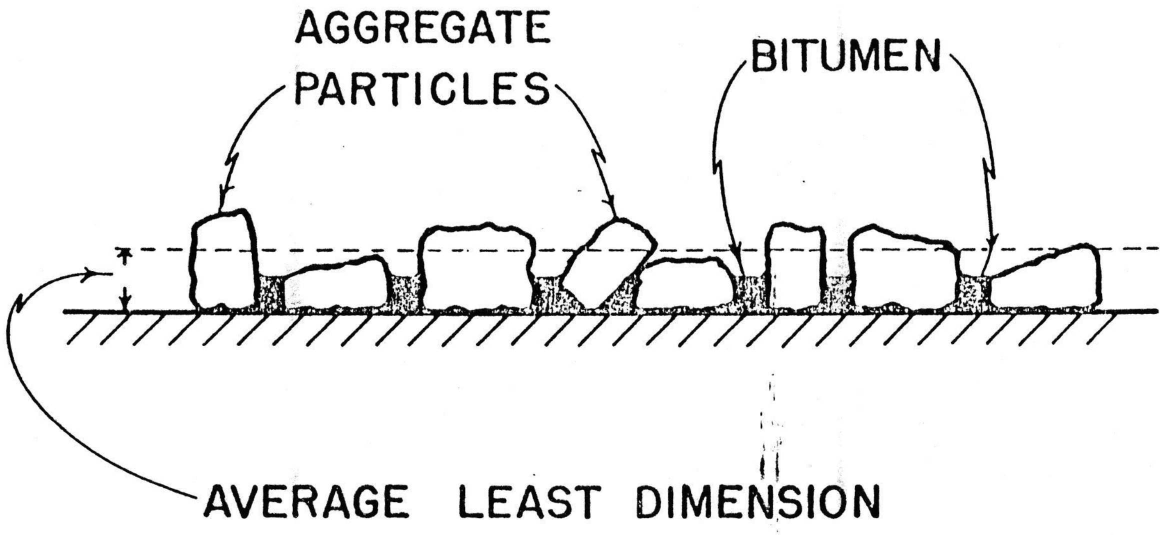


Figure 7. Haphazard Positions of Cover Aggregate Immediately After Application (16)

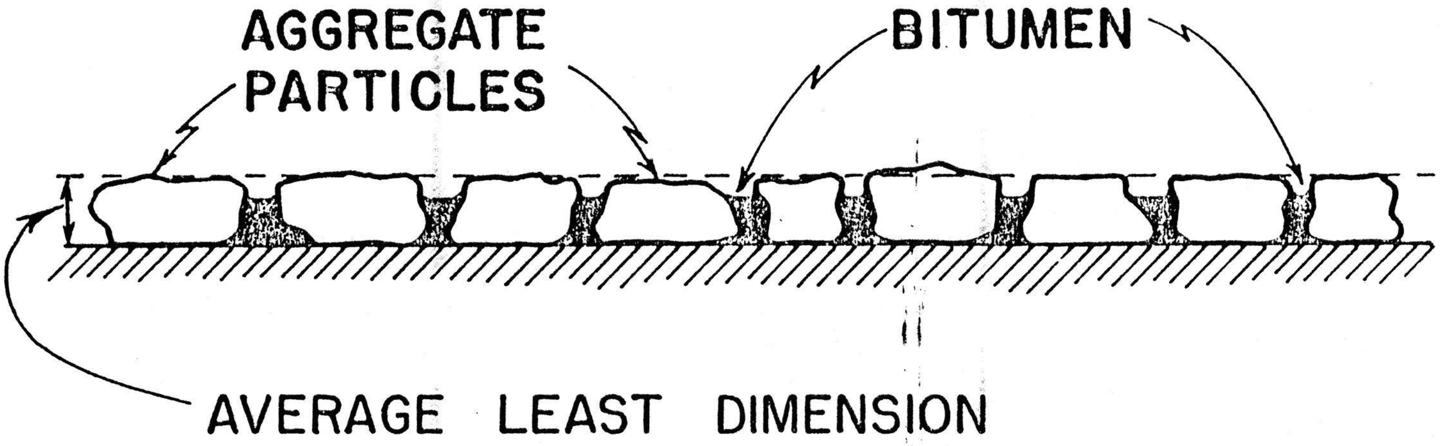


Figure 8. Ultimate Positions of Aggregate Particles After Considerable Time (16)

increase has been found to vary from 10 to 20 percent above that quantity needed to cover the surface. Some authors feel that excess cover stone causes more damage than if just the required amount of stone is applied (14, 18, 19). Excess cover stone promotes a double layer of stone particles which in turn causes ravelling, potholing and the formation of corrugations. An excess of aggregate also increases the amount of fine aggregate. The excess fines tend to go to the bottom and become embedded in the asphalt or blot the surface of the asphalt thereby preventing the embedment of the coarse aggregate particles and allowing a large percent of the coarser particles to be subjected to whip-off. The resultant seal coat is very likely to become streaked under traffic action as the smaller particles become submerged. Loose aggregate will also cause loosening of the aggregate already firmly embedded in the bitumen. The general tendency is to overapply aggregate when it is really wiser to slightly underapply (18).

Quality

In addition to aggregate mineral composition, particle size and gradation and quantity applied, many other qualities of the aggregate influence the performance of a seal coat. Grouped in the quality category are: particle shape and texture, strength, abrasion resistance, durability, cleanliness and adhesion characteristics.

The shape of the aggregate particles used in a seal coat greatly affect the interlocking qualities of the particles. The best interlocking qualities can be achieved by using angular particles. Cubical or pyramid shaped particles have been found to work best (14). Harris (20) indicates that a cover aggregate should be composed of at least 60 percent fractured particles. Aggregates that have a considerable amount of plates, splinters, elongated or flaky particles should not be used. The elongation index and flakiness index, which have been discussed earlier, give a good indication of excessive long or flat particles in the aggregate sample. Kearby (19) suggests that elongated or flat particles combined should not exceed 10 percent of any aggregate gradation. He considers flat particles as those particles with a thickness of less than half the average width of the particle while an elongated particle has a length greater than twice the other minimum dimension.

The surface texture is the most important single property of an aggregate used in seal coat work but is the one property least subject to evaluation and control. There is improved skid-resistance when a rough, gritty texture is provided.

Crushing of seal coat aggregate may result from one or a combination of several factors including soft aggregate, the weight of the rollers used during compaction being too heavy, or the existing surface being too hard and not allowing the new aggregate to penetrate into the surface when rolling is performed.

The aggregate's resistance to crushing depends on the type and source of the aggregate. The degree of crushing has been found to be a function of the original gradation, original size and shape of the particles, and the number of roller coverages.

The abrasion effect on seal coat aggregate can be divided into a polish and a wear phase. The polish of an aggregate occurs when the points, edges and surface roughness of aggregate particles are lost. Wear of an aggregate refers to the condition of the aggregate during the period it takes to erode the projecting particles down to a level equal to the depth of the binder. The rate of wear and polish is dependent on the particle size, shape, application rate, and hardness of the aggregate along with vehicle tire characteristics. Polishing and wear are detrimental to a seal coat surface due to a considerable reduction of pavement skid-resistance.

A surface such as a seal coat should be reasonably resistant to the abrasive effects of vehicular traffic. A number of recommended Los Angeles abrasion test requirements can be cited. Most sources specify a maximum abrasion loss of 35 to 40 percent (5, 16).

Since aggregate particles in a seal coat are not covered by a protective asphalt film as they are in bituminous mixes, the aggregate undergoes considerable exposure to the elements of nature. The durability of aggregates will vary from location to location and since weathering and the effects of traffic usually cannot be predicted, the durability is one of the most difficult aggregate properties to determine. Several tests, such as the sodium and magnesium sulfate soundness tests and freezing and thawing tests, have been used to indicate the durability. Some aggregates contain foreign substances. This deleterious material may be reduced but there is a limit beyond which such operations are neither feasible nor economical. Unless the amount of this material is within acceptable limits, it is unsuitable for use as seal coat aggregate. Typical objectionable materials are vegetation, shale, clay lumps and clay coating on the aggregate particles.

The cleanliness of the aggregate may often be determined by visual inspection for clay coated particles. A washed sieve analysis provides positive proof. Evaluations should be made of the effect material finer than the No. 200 sieve and organic matter present in the aggregate have on the asphalt coating of the aggregate particles (20).

Emulsion - Aggregate Systems

Theory

If the charge on the emulsion and the aggregate are different, one may expect good coating and adhesion. The chances of obtaining a good aggregate-emulsion bond when the charges on the materials are the same are considerably poorer. This concept explains why anionic emulsions, which contain negatively charged asphalt particles, have been used with electropositive aggregates such as limestones. The differences in surface charges between the emulsifed asphalt and the aggregate surface promotes adhesion. This situation is shown in Figure 9. In this system, the anionic emulsifier acts as a bridge between the asphalt and aggregate. When an anionic emulsion is used with a siliceous aggregate, the aggregate, being negatively charged, repels the negatively charged emulsion. No charge neutralization takes place and the anionic emulsifier cannot function as a bonding agent. The emulsion drains off the aggregate instead of plating out and coating.

According to Mertens and Wright (11), good adhesion between electronegative aggregates and an emulsified asphalt became feasibile when cationic emulsions became available. These emulsions, because of their positively charged asphalt particles, are attracted to the surface of the electronegative aggregate as shown in Figure 10. As the emulsifier is drawn to the surface of the aggregate, the nonpolar tail of the emulsifier pulls the asphalt to the surface. Consequently, the cationic emulsion also functions as a bridge or bonding agent.

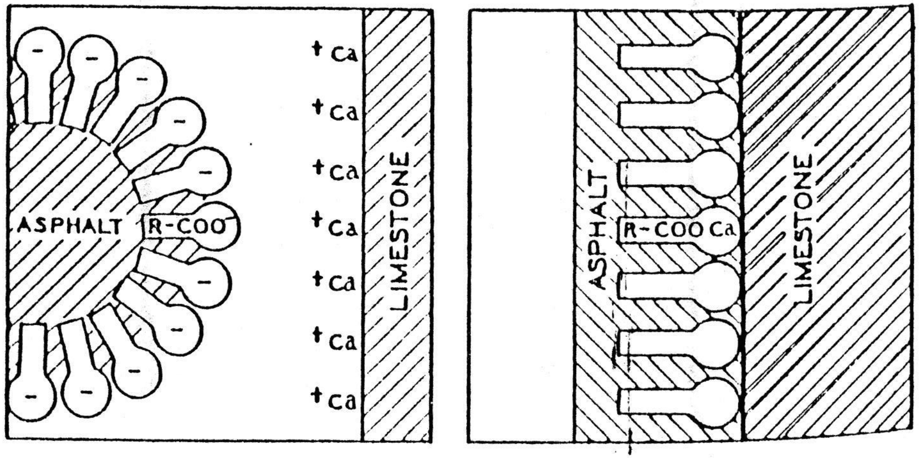


Figure 9. Action of an Anionic Asphalt Emulsion on Calcareous Aggregates (11)

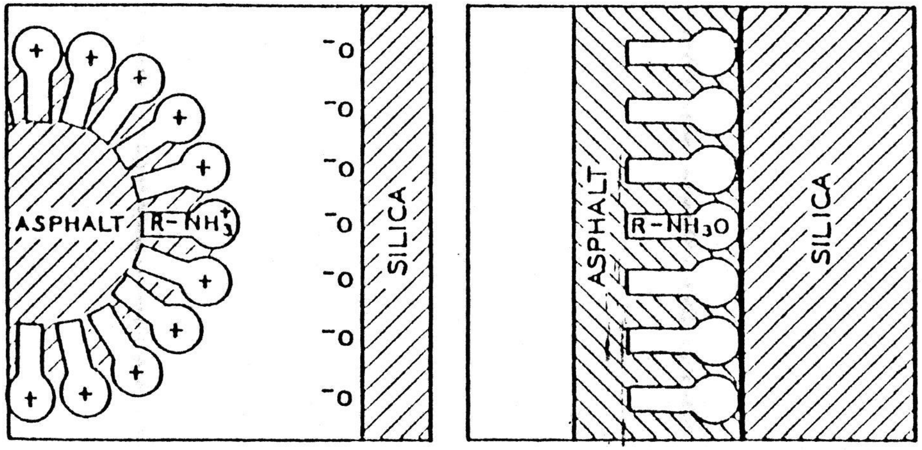


Figure 10. Action of a Cationic Emulsion on Silica (11)

Mertens and Borgfeldt (6) reported the results of tests on a wide variety of aggregates, comparing cationic and anionic emulsions. Out of 16 samples, the cationic emulsions coated and adhered to 15 of them with a rating of 90 percent or better. The anionic emulsions had a rating of 90 percent or better on only 6 of the 16 samples. They also reported data showing that cationic emulsions can be used on many limestones as well as on siliceous gravels, yielding excellent seal costs.

Although either type of emulsion may be used with mixed aggregate, the cationic emulsion seems to be somewhat more versatile for they can be used with a broader range of aggregate types than anionic emulsions. The exact range over which each type of emulsion can be used has not been fully determined but Figure 11 gives the concept of range for each emulsion and the approximate area of overlap where either type may be used.

Various theories have been presented to explain why cationic emulsions provide better adhesion and aggregate retention than an anionic emulsion. These theories include the hydration theory, substantivity and the magnitude of particle charge.

The hydration theory implies that because of the type of emulsifying agent used in cationic emulsions, cations such as sodium or potassium bind water firmly; and if the ions are small, shells of water involving hundreds of molecules of water form around the cation. Anions hydrate much less readily. Consequently, the chloride ions interfere much less in the reaction and absorption of the cationic emulsifier on the aggregate surface than do sodium or potassium ions with asphalt emulsifiers. As a result of the water shell the cationic emulsifier can approach the aggregate surface so that the Van der Waal force of attraction eventually comes into effect.

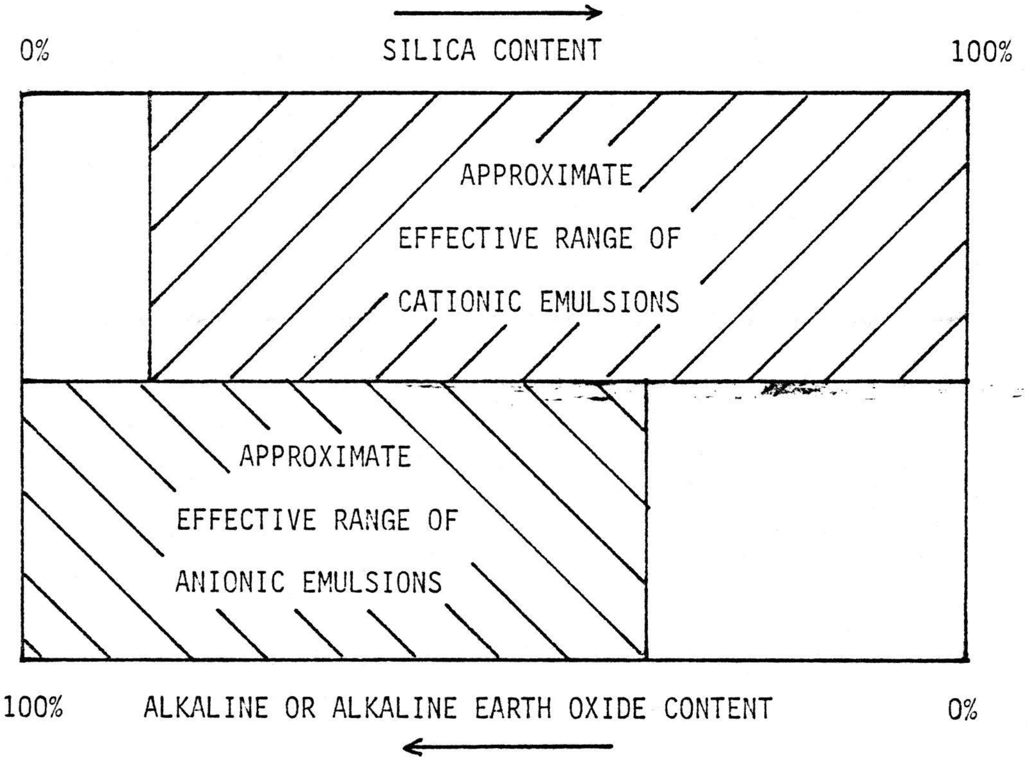


Figure 11. Approximate Effective Range of Cationic and Anionic Emulsions on Various Types of Aggregates (11)

Substantivity is a property of cationic emulsions which allows the emulsion to break rapidly on contact with aggregates and at the same time deposit a thick coating of asphalt on the aggregate. This action varies directly with the pH of the emulsion. For a cationic emulsion-aggregate system, the plating action of the asphalt is greater if the aggregate is damp. The moist aggregate allows the surface to become charged by the dissolved water soluble ions that satisfy the charge sites of the aggregate particle.

The force between two charged bodies varies directly as the product of the charge. The charge on a cationic emulsion particle is twice that of an anionic emulsion particle; therefore, this greater charge force enhances plating action and enables cationic emulsions to take advantage of a smaller aggregate charge and still give results equal to or better than anionic emulsions (6).

Performance-Defects

In nearly all countries of the world, a high percentage of seal coats are providing only a fraction of the serviceability of which they are capable (16). This is due to inadequate and often careless design and construction procedures. The four most serious defects in seal coats are streaking, use of too much asphalt, use of too little asphalt and the loss of cover aggregate.

Streaking is caused by a lack of uniformity in the applied quantity of binder. When too much binder is applied the excess rises to the surface, sometimes covering the aggregate, giving the road a black color, and causing a flushing or bleeding that results in dangerous conditions in wet weather due to a lack of skid resistance. The use of too little residual asphalt results in a loss of cover aggregate. Not enough binder is present to hold the aggregate in place. The loss of cover aggregate can be caused by the selection of the wrong grade of binder for the prevailing conditions, a lack of uniformity across the surface, not enough asphalt applied to the surface, considerable delay between spraying the binder and applying the cover aggregate, a rainstorm soon after construction, fast moving traffic too soon after construction, or poor quality aggregate.

Each of these defects may occur in a seal coat regardless of the quality of the asphalt cement or aggregate used. A distinction should be made, though, between a defective seal coat and a structural failure of the underlying surface. Crawford (21) believes a seal coat will fail in its first year if it is going to fail at all. The seal coat will be exposed to all the traffic and environmental conditions, such as freeze-thaw and spring breakup, during the first year. Many times a seal coat has performed badly or has been rated poorly because of a poorly maintained or inadequately constructed or designed base.

Factors Related to the Asphalt

Amount. There is an optimum amount of asphalt that must be used in the construction of a seal coat so that the surface will perform correctly. A minimum amount is needed so that the aggregate will be firmly held in place. On the other hand, there is a maximum amount since an excess of bitumen will result in bleeding, a blackening of the surface, and low skid resistance when wet.

The application of insufficient asphalt leads to the loss of cover aggregate because not enough bitumen has been applied to cement the aggregate particles into place. Sometimes the surface on which a seal coat is to be applied is so porous that a large portion of the asphalt soaks into it. The use of too little bituminous binder occurs a great deal less frequently than the application of too much (16).

Excess asphalt extrudes upward onto the pavement surface and is the black, sticky surface condition that is commonly called flushing, bleeding or fattening. The application of too little cover stone or a loss in a portion of the cover aggregate will result in a bleeding surface. A flushed surface can result from the assumption that seal coats made from a graded aggregate should be constructed one-stone particle thick, as is the usual practice with a one-size aggregate cover. When this practice is followed, the quantity of asphalt required to cement the large particles tends to submerge the smaller particles. Tires make contact with the binder in these areas, a situation which should not be allowed to happen, and a black surface results. A considerable amount of the coarser aggregate particles are lost since there is an insufficient amount of binder left to retain the aggregate which in turn results in an overall deficiency of cover aggregate in the seal coat (16).

When a seal coat is applied, the absorption of the asphalt by the existing bituminous surface must be taken into consideration. This absorption is based on the average condition of the existing surface as it appears in the wheel paths. This absorption was found to vary from no additional asphalt for a smooth condition to 0.10 gal/sq. yd. A test to determine the absorption of an old bituminous surface has been developed by Zube (22). A defined area of the pavement to be tested is kept constantly wetted with a water and detergent solution for two minutes.

The amount of solution used is calculated and the relative permeability is determined. Even though the porosity of the pavement and the relative need for a seal coat is found, Zube believes that a quantitative measure of asphalt absorption can be made. A reduction in the asphalt application rate may be necessary when the existing surface exhibits excess asphalt or a bleeding condition on the surface. Allowances are not usually made for absorption of the asphalt by the aggregate (16).

It must be recognized that the asphalt requirement is based on the assumption that the underlying surface is firm and unyielding and the aggregate will not be forced down into the old surface by traffic. The penetration of the aggregate into the old surface may happen on a previously overasphalted or bleeding area. The voids in the cover aggregate are reduced and the old roadbed must be fixed or a reduction in the asphalt content must be made. Marek and Herrin (23) have developed a test for surface hardness at a given temperature using a standard Marshall compaction hammer and a one-inch diameter steel sphere. The sphere is placed in contact with the underlying surface and is subjected to five blows of a 10 pound weight falling a distance of 18 inches. The vertical distance from the plane of the surface to the lowest point in the depression is measured with a penetrometer.

Uniformity of Application. Streaking results when alternate longitudinal strips of a seal coat contain different quantities of the asphalt, due to a lack of uniformity of application of the emulsion across the surface of the roadway. This situation can result from an under-asphalted mixture, an excess of asphalt, or from improperly maintained, improperly adjusted, or carelessly operated bituminous distributors. Another frequent cause of streaking is applying the emulsion at too low a temperature so that it is not fluid enough to fan out properly from the nozzles on the spray bars. At high temperatures, the emulsion may run (16).

Many tests have been used to determine or correct the longitudinal and transverse variability of the asphalt application rate. Most of these tests include the calibration of distributors but Mahone and Rundle (24), along with Zube (22), advocate the use of a cotton pad test to evaluate field application rates. In this test, a series of two-inch cotton pads are attached to a panel and then placed either longitudinally or laterally on the road prior to the first distributor pass. The pads are picked up and weighed and the percent variation from the design quantity is determined. Mahone and Rundle recommend that the variation of asphalt from the design quantity should not vary more than plus or minus eight percent.

Pavement Temperatures. The viscosity and aggregate retention characteristics of an asphalt material vary inversely with the temperature of the pavement surface. When the asphalt is in a fluid state, it is unable to retain aggregate under traffic. To prevent early or subsequent loss of aggregate, the bitumen should possess qualities which would prevent softening of the material under a normal field temperature range. In order to do this, some agencies are fluxing hard asphalt cements and emulsions with kerosene to produce desirable spraying and binder viscosities (25).

Laboratory and field studies have shown that the actual application temperatures of seal coat bitumen have little effect on the time or depth of penetration. The comparatively small quantity of asphalt emulsion, upon coming in contact with the old surface, almost immediately acquires the temperature of the mat and its fluidity is then dependent on the surface temperature. Hank and Brown (26) indicate the temperature of the road surface, not the distributor application temperature, governs the temperature of the asphalt film and, therefore, its properties relative to bonding and retaining aggregate. It has been indicated that in areas where emulsions are applied at temperatures at or below 140 F, the application and subsequent performance is generally good. At application temperatures in the range of 160 to 190 F, the resulting seal coat is generally beset with a number of problems (27).

Effect of Asphalt Grade. Most of the literature indicates that the base asphalt should be in the 100-300 penetration range (5, 16, 17, 25). Arizona, which has some of the longest, hottest summers in the United States, has used high penetration grade base asphalts, up to 350 penetration, in all of their seal work for nearly 20 years without any tendency toward bleeding (5). Lohn and Nevitt (18) had originally indicated the use of a base asphalt in the penetration range of 50. While harder asphalts give better retention characteristics for the aggregate originally embedded, the softer ranges will permit a higher percentage of embedment initially. There are other known advantages in the use of softer asphalts. These are higher resilience, lower temperature susceptibility, and a longer term of effective resistance to the action of the elements (25).

From tests they have conducted, Hank and Brown (26) concluded that, with other factors remaining the same, aggregate loss shows a gradual increase with a decrease in penetration of the base asphalt. The harder grades have a long time advantage in that their stronger bond tends to prevent displacement of aggregate once it is embedded. They also concluded that the belief that bleeding can be prevented by the use of a harder base asphalt cement in cutbacks and emulsions has been refuted by laboratory and field observations. Any time that the application rate and final retention of aggregate is insufficient for the amount of asphalt used, bleeding will occur as soon as weather and traffic considerations are favorable for bringing the asphalt to the surface. The use of a harder grade of asphalt merely causes a delay in the process.

Asphalt-Aggregate Adhesion

The electrochemical process is one of many ways that explain the method by which aggregate sticks to the asphalt binder. Since the emulsifying agent used in emulsions remains in the asphalt after the water has evaporated, it may be the primary means of maintaining a bond between the asphalt and aggregate, but other adhesion principles must be considered.

Adhesion is defined as that physical property by which one body sticks to another of a different nature. Four theories on the cause of adhesion--chemical reaction, mechanical adhesion, surface energy and molecular orientation--have been summarized (28). The chemical reaction theory states that acidic components of the asphalt react with basic minerals of the aggregate. This theory does not hold true in all cases since good adhesion has been reported between asphalts and siliceous aggregates. Aggregate properties that affect mechanical adhesion include surface texture, absorption and porosity, surface coating and area, and particle shape. It has been observed that rough, irregular-surface aggregates have better asphalt retention qualities than smooth surfaced aggregates. Surface energy is related to the surface tension of the asphalt and interfacial tension that develops between the asphalt and the aggregate. Adhesion tension is a phenomenon that takes place on the surface of the materials and depends on the closeness of contact, time of contact and the mutual affinity of the two materials. Asphalt molecules also have a tendency to orient themselves, over a period of time, to satisfy the energy demands of the aggregate.

Seal Coat Design Methods

The design of seal coats has been accomplished for many years on a trial and error basis. The design equations used give the amount of residual asphalt to be applied and the quantity of cover aggregate required. A large number of design methods have evolved over the years. A few of the more relevant design procedures, with their year of publication, include: Hanson (1935), California (1949), Nevitt (1951), Kearby (1953), Lovering (1954), McLeod (1960, 1969, 1974), Marek (1971), and the Asphalt Institute (1979). Some of the salient features of these design methods follow.

Early Methods

The classic work on the design of seal coats was published by F. M. Hanson, A New Zealand engineer, in 1935 (29). His principles of seal coat design are so fundamental that they have been used by a number of engineers in developing other methods of designing seal coats.

Realizing that existing methods of designing seal coats were unsatisfactory, Hveem, Lovering, and Sherman, of the California Division of Highways, were one of the first groups in the United States to analyze the seal coat design problem (30). Armed with Hanson's seal coat study and much of their own field data and observations, they determined that Hanson's method of determining the average least dimension of an aggregate was not feasible. Hveem et al. found that the volume of the screens which would produce a layer one-stone thick could be related to an "effective maximum size" as long as no appreciable fine material was used. The effective maximum size is determined as the theoretical sieve size in inches which would allow 90 percent of the aggregate to pass through the sieve openings. They were also some of the first engineers to realize that not all variables are revealed by the sieve analysis and that other variables, such as the shape and surface of the aggregate, should be considered. Hveem et al. also believed that the whip-off allowance factor should not be constant but should be based on spreading equipment and other factors.

In 1951, H. G. Nevitt (14) presented several equations for the "correct" determination of aggregate and bitumen quantities. In doing so, he made several assumptions which influence the design quantities.

Nevitt's formulas depend on many factors in which no procedure has been established to provide a numerical value that can be used in design equations. Nevitt has stressed that the theoretical values derived from the equations are too high even though many others have stated that the equations give accurate estimations of required quantities.

One of the most common methods for designing seal coats is based on the work of Jerome P. Kearby (19). Its applicability is primarily limited to one-size aggregates with a reasonable tolerance for undersize or oversize aggregate. With an aggregate coverage of one stone in depth, the quantity of aggregate is fixed and the average thickness of the mat is termed the "effective or average mat thickness." Kearby suggests two methods for determining the average mat thickness, one of which is based on a sieve analysis of the aggregate. The percentage of aggregate for each individual screen size is multiplied by the average mat thickness. The other method is the "test board" method. A board, usually one yard square, is covered with a sufficient quantity of material so that full coverage of the area one stone in depth is obtained. The weight of aggregate on the board is divided by the area of the board and the spread quantity is obtained.

The quantity of binder required was related by Kearby to the amount needed to embed the aggregate sufficiently in the asphalt so as to hold the aggregate firmly in place, as shown in Figure 12. Once the percent embedment is determined from the curve in Figure 12, the required amount of binder can be computed from the average mat thickness. Although the required volume of binder can be determined by the mathematical computations as shown below, Kearby has devised a nomograph for these calculations which is presented in Figure 13.

The design quantities can be determined from the following procedure.

1. Determine the average mat thickness by the test board or sieve analysis method.
2. Find the loose unit weight in pounds per cubic foot (W).
3. Theoretical spread ratio = 36/average mat thickness.
4. Aggregate application rate = W (27/Spread Rate) in pounds per square yard.
5. Find the percent embedment from Figure 12.
6. Depth of embedment = (% embedment) (average mat thickness)
7. Percent voids in aggregate = (1 - (W/(G X 62.4))) X 100

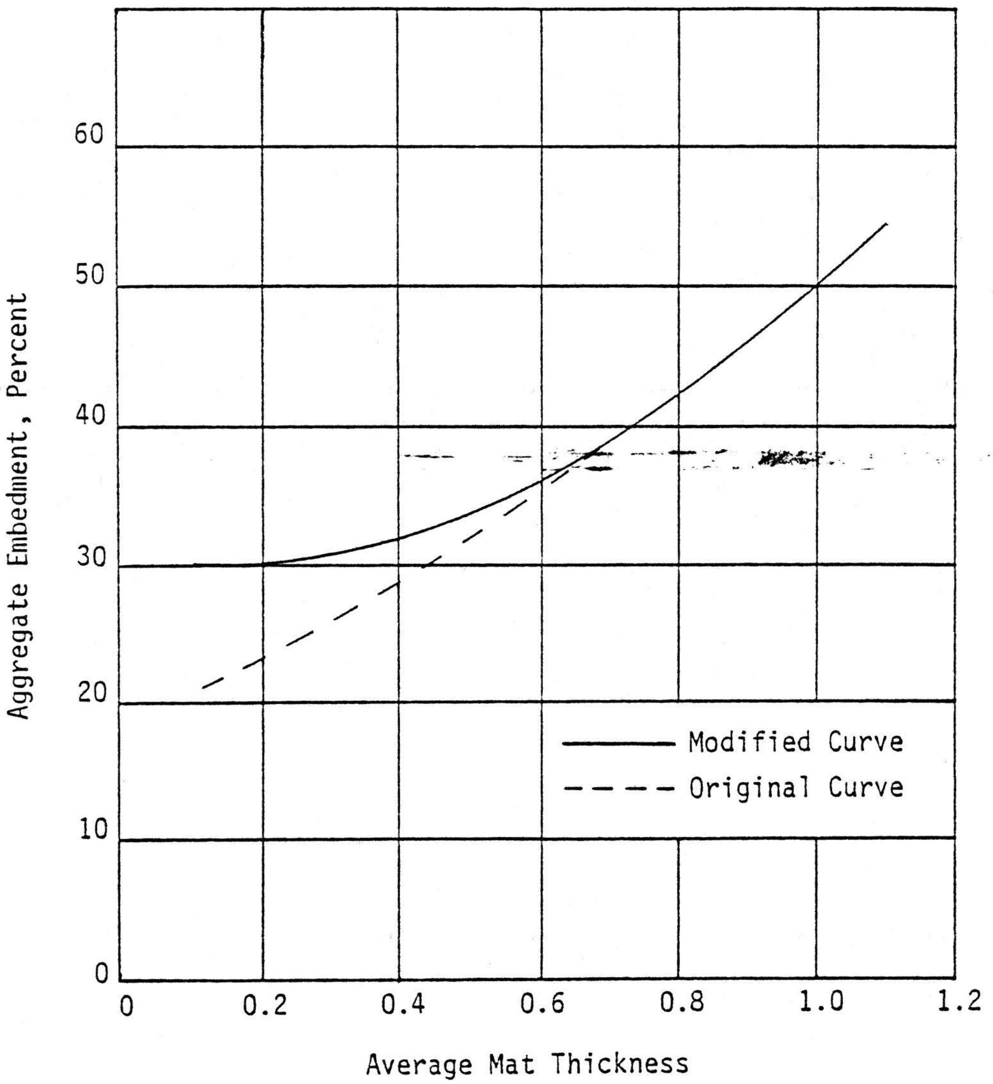
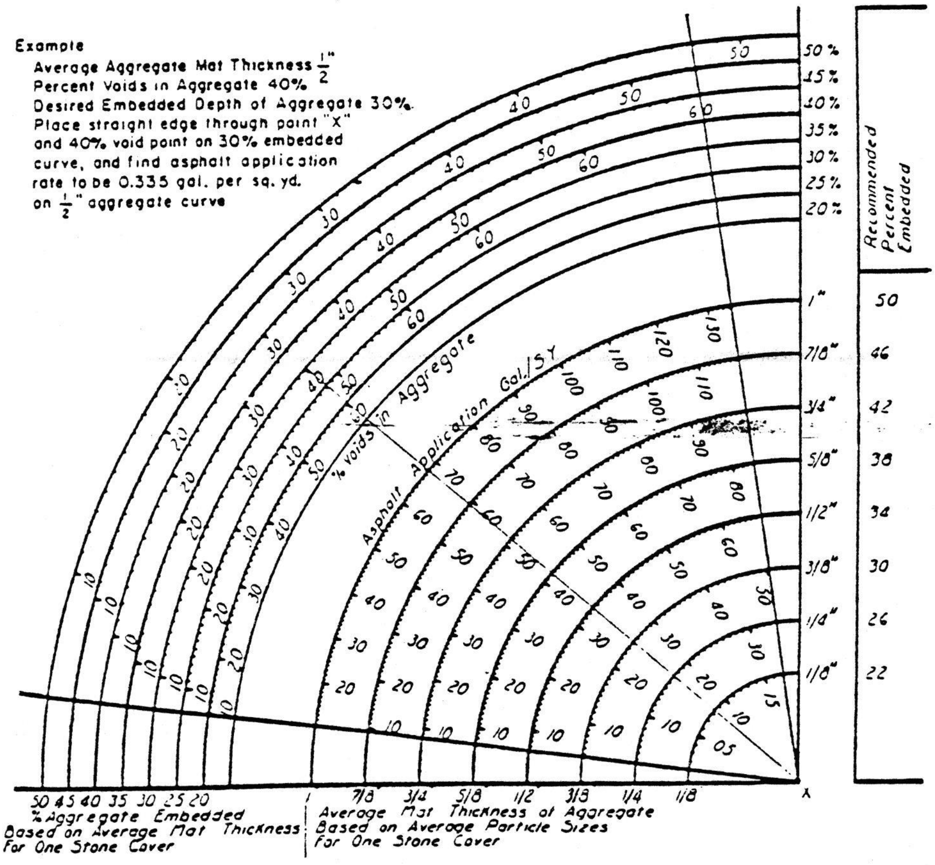


Figure **12.** Relation of Percent Embedment to Average Mat Thickness for Determining Asphalt Quantity for Kearby Design Procedure (19)



Example

Average Aggregate Mat Thickness $\frac{1}{2}$"
Percent Voids in Aggregate 40%
Desired Embedded Depth of Aggregate 30%.
Place straight edge through point "X" and 40% void point on 30% embedded curve, and find asphalt application rate to be 0.335 gal. per sq. yd. on $\frac{1}{2}$" aggregate curve

Figure 13. Kearby Nomograph for Determining Binder Application Quantity (19)

8. Residual asphalt application rate = (Depth of aggregate embedment/12) X 67.32 X (Percent voids in the aggregate) in gallons per square yard.

W. R. Lovering decided that direct measurement of the aggregate and a one-size aggregate gradation as developed by Hanson was not very practical (30). Accordingly, grading tolerances were established to allow for undersize and oversize particles greater than a No. 10 sieve. In order that a graded aggregate could be used, Lovering determined that there was a satisfactory correlation between the loose volume of the cover stone required to produce a layer one stone thick and the "mean particle diameter." The mean particle diameter was defined as the spread modulus and is the weighted average of the mean size of the largest 20 percent, the middle 60 percent, and the smallest 20 percent. From his observations, Lovering determined that a factor of 0.85 to 0.95 times the spread modulus would provide the proper quantity of screenings with an allowance for both compaction and whip-off.

Lovering was influenced by Hanson's work in regard to the amount of voids in the aggregate which should be filled with binder. He concluded that the quanitity of binder material required is equal to 0.56 times the cubic feet of cover stone per square yard exclusive of the allowance made for whip-off.

Design Methods, 1960 - Present

N. W. McLeod has published seal coat design information for cut-back asphalts and asphalt cements in 1960 (16), a general method of seal coat design in 1969 (31) and extended his method to include asphalt emulsions in 1974 (32). McLeod's procedure is based on Hanson's work. McLeod has used the modifications of the County Roads Board of Victoria, Australia, in regard to varying bitumen quantities with traffic volumes. The County Roads Board also uses the flakiness index to determine the least average dimension of the aggregate particles. The McLeod method is one of the most commonly used methods for determining the design quantities of asphalt and aggregate. The design procedure may also be found in the Asphalt Institute's Manual No. 19, "Basic Asphalt Emulsion Manual" (8).

Marek and Herrin (23) have developed a seal coat design method which takes into consideration such design variables as aggregate size, aggregate shape, the aggregate source, the fines in the aggregate and temperature. This method is called the voids concept design method. The embedment of new aggregate into the underlying surface and the compactive effort are new variables which have not been taken into consideration in other design methods. The bitumen quantity is adjusted to take into account aggregate fines so a graded aggregate can be used.

Marek and Herrin feel that a significant improvement in older design methods has been found since the voids concept design method takes into account the nonlinear variation in the volume of the voids with depth within an aggregate layer. A simplification of the design procedure to account for the shape of the aggregate by the use of different voids curves for crushed stone and gravel is also used. The authors recommend a fairly large-size aggregate and a limit on the material passing the No. 4 sieve.

The assumptions used by Marek and Herrin are:

1. The quantity of cover aggregate required is generally that amount needed to form a layer one particle in depth over the surface being sealed.

2. During construction and under subsequent traffic, the aggregate particles tend to reorient until they present their least dimension in the vertical direction.
3. Because of reorientation of the aggregate, the quantity of binder and, to a certain extent, the quantity of aggregate needed are related to the average least dimension of the aggregate.
4. The basic quantity of binder material to be used is that amount required to fill the voids existing between the aggregate particles to an optimum depth. Therefore, the amount of binder needed is a function of the volume of the voids in the cover aggregate layer that, in turn, is influenced by factors such as aggregate gradation, maximum size, aggregate shape and surface texture, and aggregate embedment into the underlying surface.
5. In order to determine the spray quantity of binder material needed, the basic quantity of binder material must be adjusted for aggregate absorption characteristics, characteristics of the underlying surface, amount of volatiles present in the emulsion and an increase in the volume of the binder when heated for spraying.

The design method requires the aggregate quantity to be determined by the test board method or the weighted average of the individual sieve sizes to determine the average least dimension of the aggregate. When the weighted average method is used, the basic aggregate quantity can be determined from the following equation:

$$\text{Basic Aggregate Quantity} = 24 \times \text{ALD} \times G$$

where:

ALD = the average least dimension of the aggregate in inches

G = the bulk specific gravity of the aggregate

The equation derives only the basic quantity and does not take particle shape into consideration. The authors recommend an increase of 6 to 15 percent to allow for whip-off.

The total percentage of voids at complete submergence (1.25 ALD) is determined from Figures 14 and 15 which illustrate the relationship between the percentage of voids and depth as a percentage of ALD for crushed stone and gravel. The total percentage of voids is then applied in the following equation:

$$V = VT + 14.8 - 29.5 (ALD)$$

where:

V = the total percentage of voids to complete submergence in an aggregate layer with a specific ALD

VT = the percentage of voids at complete submergence for an aggregate with an ALD of 0.5

The reduction of total voids is determined to account for aggregate embedment into the underlying surface. Information about the underlying surface must first be obtained. This information is readily obtained by conducting a field test for hardness and by using the data shown in Figure 16. The test for surface hardness at a given temperature is performed by using a standard Marshall compaction hammer and a one-inch steel sphere. The sphere is placed in contact with the underlying surface to be tested and is subjected to five blows of a ten pound weight falling eighteen inches. The vertical distance from the plane of the surface to the lowest point of the depression is measured with a standard penetrometer. This distance is obtained from Figure 16 which is then applied in Figure 17 to the percent reduction in voids to account

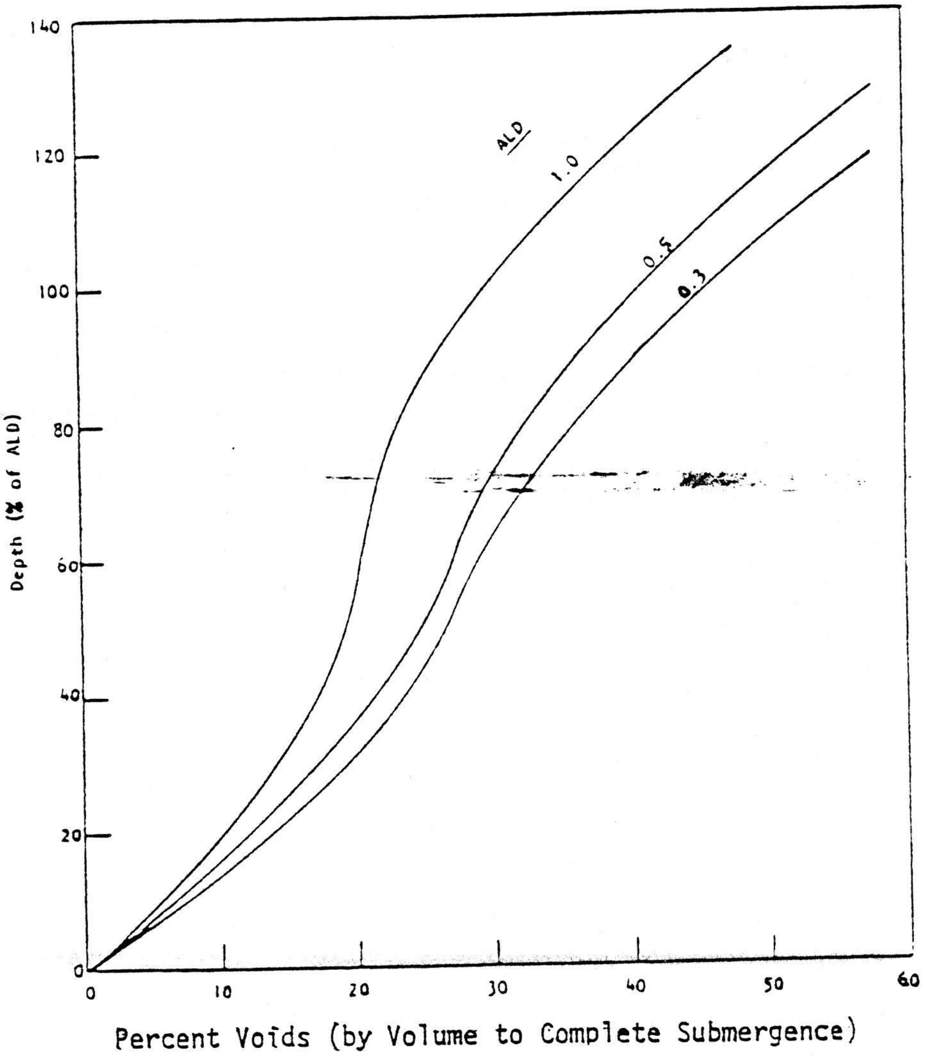


Figure **14.** Relationship Between Percentage of Voids and Depth as a Percentage of ALD for Crushed Stone (23)

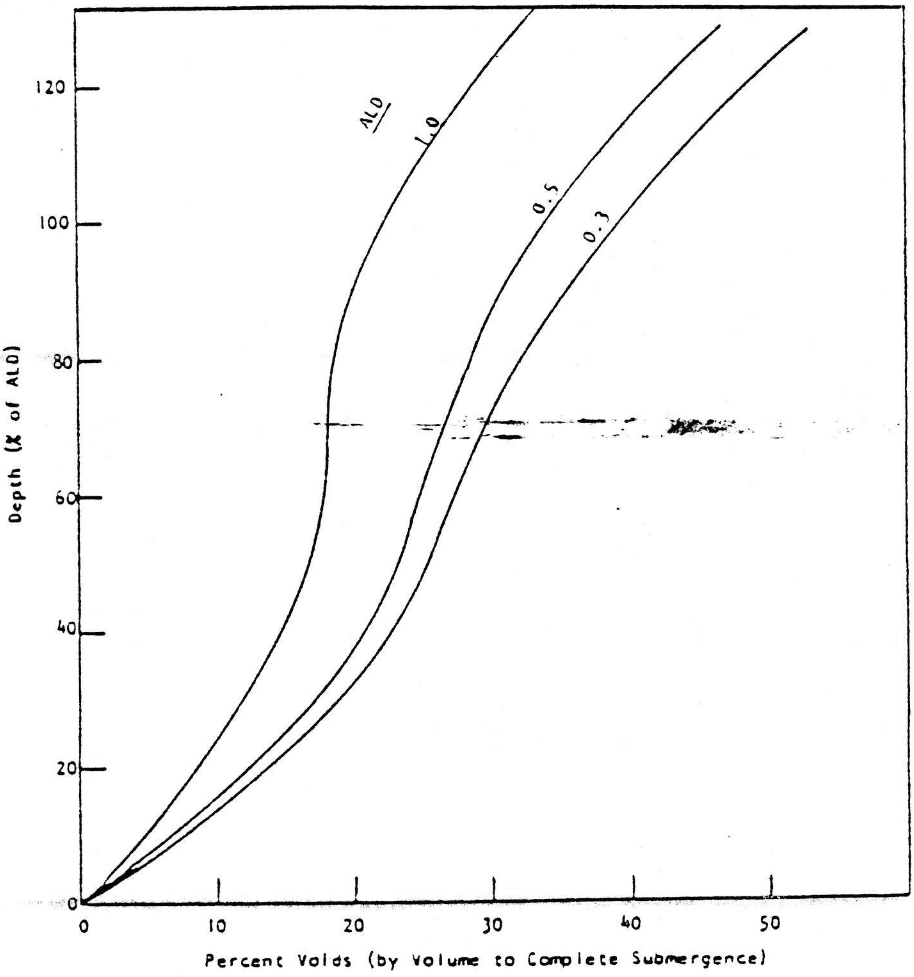


Figure 15. Relationship Between Percentage of Voids and Depth as a Percentage of ALD for Gravel (23)

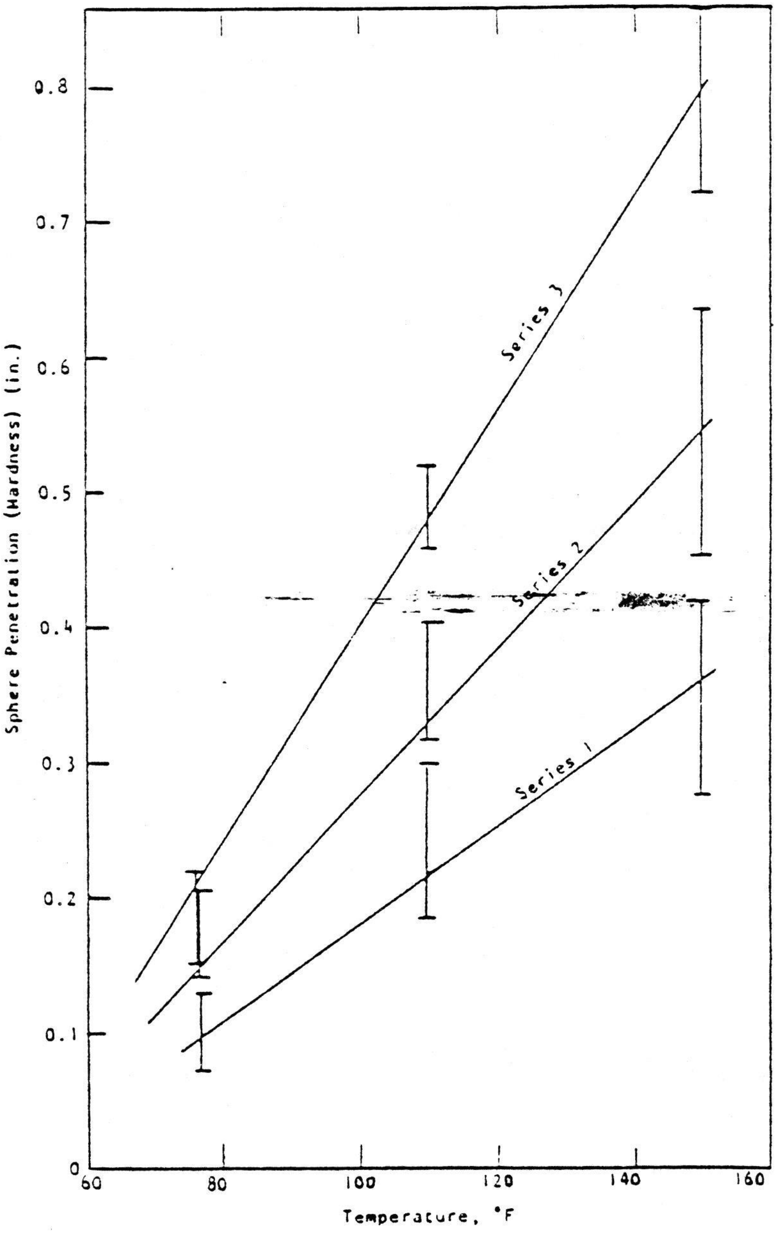


Figure 16. Relationship Between Hardness of Underlying Surfaces and Temperature (23)

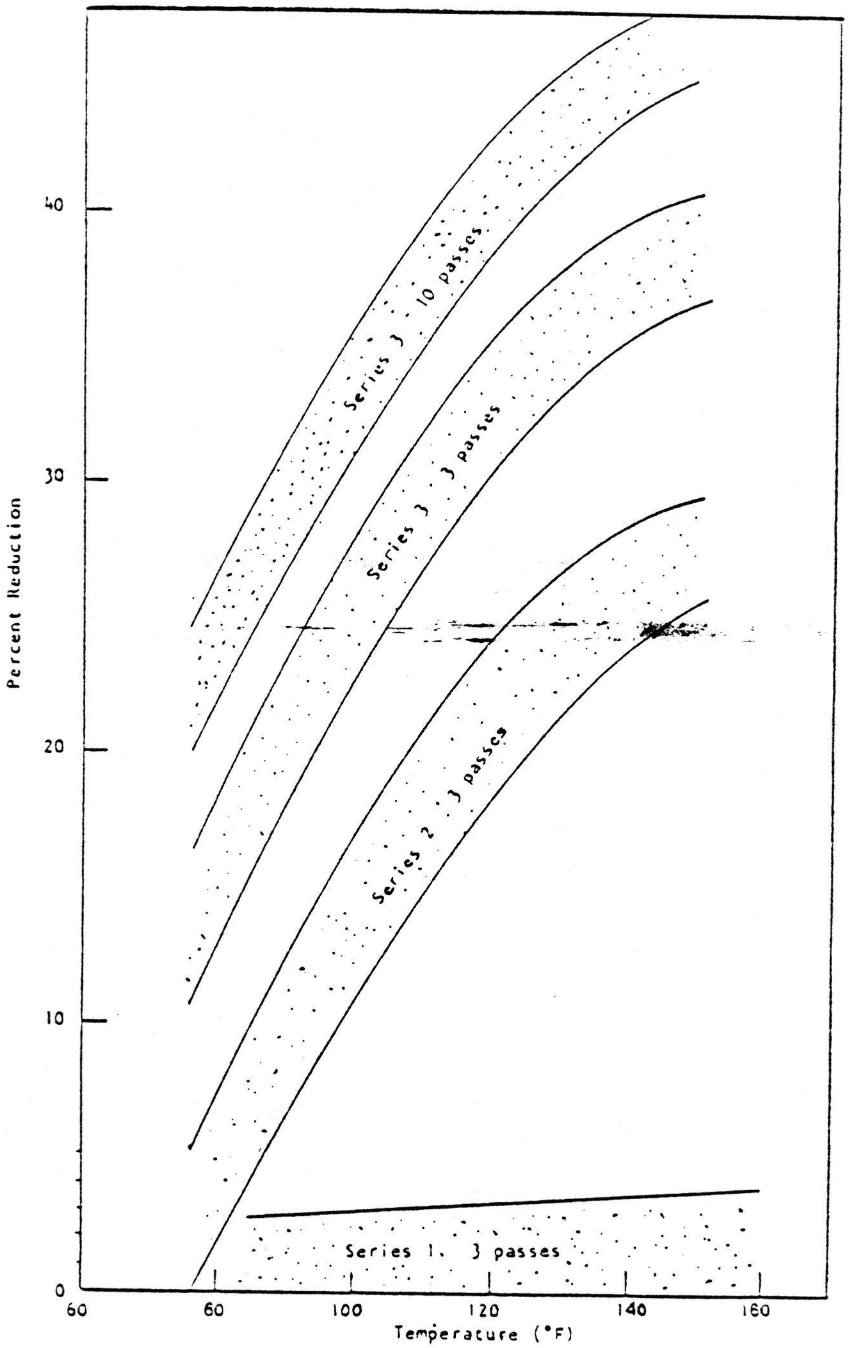


Figure 17. Percentage Reduction in Void Space vs. Temperature of Underlying Surface (23)

for embedment into the underlying surface is computed by the following equation:

$$VE = R/100 \times VT$$

where:

VE = is the amount that the total percentage of voids must be reduced to account for embedment

R = the percent reduction from Figure 18.

A reduction of the total voids is necessary to provide adequate skid resistance and aggregate retention. Marek and Herrin state that about 40 percent (by volume) of the aggregate should be exposed and the voids in the aggregate should be filled to a depth equal to or greater than 60 percent of the ALD of the aggregate. The amount that the total voids must be reduced is computed as follows: select either Figure 14 or 15 depending on the type of cover aggregate, enter the appropriate figure with the depth D based on complete submergence, and compute the amount of reduction of the total voids by the following equation:

$$VS = V - VD$$

where:

VS = the amount that the total percentage of the voids must be reduced to provide satisfactory depth of binder to provide adequate skid resistance

VD = the percentage of voids to depth D determined from Figure 14 or 15.

The uncorrected basic quantity of the binder can now be determined from the following equations:

$$VC = V - (VE + VS)$$

$$Q = VC/100 \times ALD\ 7.03$$

where:

Q = the uncorrected basic quantity of the binder in gallons per square yard.

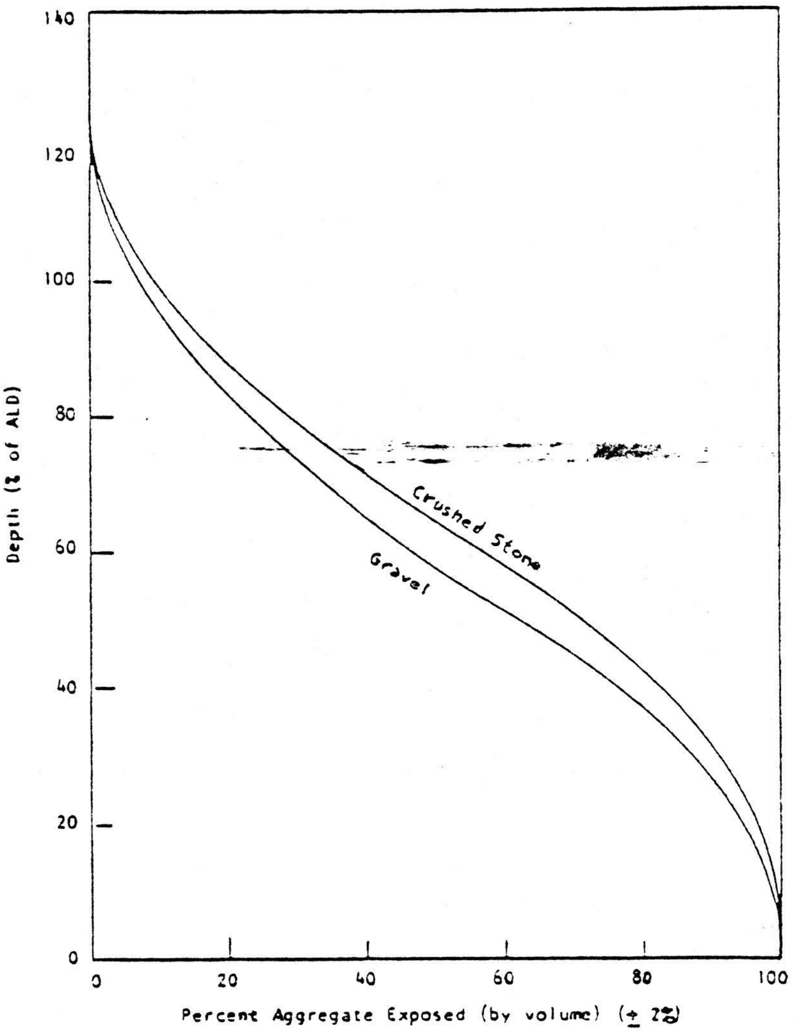


Figure 18. Relationship Between Percentage of Aggregate Exposed and Percentage of Depth Regardless of Aggregate Size When on a Rigid Base (23)

The fines in the aggregate that pass the No. 4 sieve materially influence the volume of the binder needed. The binder correction for the fines can be computed from the equation:

$$QB = Q - [0.12 \times (W/G)]$$

where:

W = the weight of minus No. 4 material

G = the specific gravity of the minus No. 4 material.

The final binder application rate is determined by subtracting QB from Q.

The authors also indicate a correction must be made for volatiles in the emulsion or cutback, the spraying temperature and the amount of binder absorbed by the underlying surface.

Seal Coat Construction

A seal coat should not ordinarily be applied to an existing old bituminous surface unless it is structurally capable of carrying the traffic volume expected during the life of the seal coat. Unless deficiencies and defective areas in the old surface can be corrected by cold mix patching or fog sealing with an emulsion, they should be cut out and replaced with sound material. If the fault originated in the base course or was caused by a base course failure, the base should be excavated, replaced and compacted. Potholes should be excavated until solid material is reached and then filled with a bituminous premix. Shoulders should either be built up or cut down as required to restore them to their specified cross-section. Where broken edges have occurred along the old pavement, the old pavement should be restored with a premix along with the removal of hardened clay or other foreign material on the surface or near the edges. When bumps have developed on the surface due to patching, or low spots and depressions have developed due to settling of the base course, the bumps should be removed and the depressions filled. Surface cracks that are not caused by base course failures should be filled (16).

Many agencies, when encountering an extremely underasphalted or "hungry" section of the old pavement due to relatively porous, badly worn, or rough-textured areas, require that light applications of an emulsion or cutback be applied to reduce the absorption or the residual asphalt by the old surface. Likewise, extremely rich or bleeding surfaces should be corrected by burning off the excess bitumen. McLeod (16) suggests that all the preparatory work be completed at least three months before the seal coat is applied. Immediately before the seal coat is applied, the old surface must be swept clean of all foreign matter and dust (32).

Construction Methods

Asphalt application. Viscosity of the emulsion at the time of application is a crucial factor in the distribution of the asphalt and the overall performance of the seal coat. The viscosity ranges for various types of emulsions suggested by investigators are not all in agreement (25).

Some agencies require the use of building paper at the joints to limit the overlapping of the binder and aggregate between two successive applications. The paper is later removed and this prevents bumps and bleeding caused by an overapplication of asphalt and aggregate. When the binder is applied in two or more longitudinal strips, each strip overlays the previous one by one-half the width of the spray from the end nozzle of the distributor. This creates a bump in the surface to some extent and is useful in lane demarcation (16).

The procedure used in constructing a seal coat consists of spraying a uniform application of emulsion along the road surface at a specified rate, applying a uniform amount of aggregate immediately after the asphalt has been applied, and rolling within minutes after the cover aggregate has been applied. An asphalt distributor is used for the application of the binder and a self-propelled aggregate spreader is usually used for applying the cover aggregate. The procedure for checking the longitudinal and transverse distributor spread of asphalt has been standardized by ASTM as Method D 2995 (33).

Problems in the application of the binder material cause a majority of the situations where poor performance of a seal coat has been observed. This is usually caused by the improper adjustment or calibration of the distributor. McLeod (16) indicates that by providing 10 inches between the road surface and the faces of the spray nozzles and spacing the nozzles four inches center to center, triple overlapping coverage will be obtained. In addition, he states that different application rates in gallons per square yard should be obtained only by changing the forward speed of the distributor and not by varying the rate of discharge per spray nozzle or pump pressure. The exception to this rule are the nozzles at the extreme ends of the spray bar which should discharge at 1.5 time the rate of the interior nozzles. Usually larger nozzles are used in this case.

Aggregate Application. The mechanics of placing the aggregate are relatively simple. The art of placing the aggregate in a uniform layer is not so simple. Since the advent of the mechanical spreader, the placement of aggregate has been simplified and the quality of the resulting work has improved. The adjustment and calibration of all types of aggregate spreaders should be made in accordance with the manufacturers' operation manuals. Aggregate distribution rates can be closely controlled by marking off the length that each truck load of aggregate should cover. A quick check on the amount of aggregate being applied can be made by the test board method previously mentioned. A square yard box is attached to the pavement (by nails) and covered with a cloth. The chip spreader is passed over the box and the aggregate retained in the box is then weighed to determine the actual application rate (34).

It is a sound construction principle that the initial lateral position of the aggregate should also be its final lateral position, except for a small amount of movement which will occur under rolling. Any discrepancies in the uniformity of the aggregate cover should be corrected by hand methods. Excess aggregate should be picked up with hand shovels and distributed over areas lacking in sufficient aggregate. The cover aggregate should be placed immediately following the placing of the bituminous material. In fact, the sooner the better because the wetting properties of the emulsion are at their maximum condition the instant the asphalt leaves the distributor (16).

Rolling. The purpose of rolling is to force the particles of aggregate firmly into the binder and thereby assist in obtaining a rapid wetting of each aggregate particle to about one-half its depth by the binder. Harris (20) suggests that usually ten complete coverages of the roller will adequately embed the aggregate and a steel wheel roller should not be used for seal coat work. This type of roller has a tendency to crush softer aggregate particles. It also bridges across smaller depressions and fails to press the cover aggregate firmly into the binder. One of the fundamental principles of construction procedures is not to use any practice or equipment which will change the design characteristics of the material being used. The pneumatic type rollers are increasingly popular and result in even better cover aggregate retention. Loose aggregate should be swept off prior to allowing traffic to use the new seal coat.

New Seal Coat Stability

Newly completed seal coats, even when carefully designed and constructed, tend to have relatively low stability and are, therefore, susceptible to damage by fast traffic. There are several reasons for the low stability including the fact that the void space has not achieved its densest condition of 20 percent voids and the aggregate interlock has not been totally completed, mainly because of the large voids in the aggregate which still exist immediately after construction. Curing time for a new seal coat is noticeably longer in cool, damp, cloudy or humid weather and the evaporation of water from the emulsions is retarded. When rain falls on a seal coat just after construction, the aggregate is particularly susceptible to being dislodged and thrown off the road. The degree of adhesion between newly applied cover aggregate and binder may be rather low following rolling due to moisture, or a coating of dust on the aggregate, or merely because of the length of time needed to develop good adhesion between binder and aggregate over the entire area of contact between them (16). This adhesion is weakened if rain falls during or just after construction.

A number of methods are available for handling the detrimental effect fast traffic has on a seal coat immediately after construction. Some of the methods include detours, confining traffic to one lane while the other is being sealed, convoy traffic over the seal coat at speeds low enough to prevent damage and enforcing slow speed travel over the new seal coat by using flagmen, warning signs and, sometimes, police.

CHAPTER III

SEAL COAT MATERIALS AND CONSTRUCTION

During the summer of 1981 the Arkansas State Highway and Transportation Department (AHTD) maintenance sealing crews scheduled approximately 200 road sections for sealing. Samples of asphalt emulsion (all CRS-2), mineral aggregate and inplace seal coat were secured from seventeen of these scheduled projects. These samples were taken at the time when the seal coats were being constructed. In addition, samples of the asphalt cement used in the manufacture of the CRS-2 were obtained from most of the emulsion manufacturers' plants.

The inplace seal coat samples were obtained by placing a sample plate (approximately 12 in. by 24 in.) on the pavement in the center of the lane ahead of the distributor truck. After the rolling process was completed, the sample plate was removed from the road, wrapped in manila paper and transported to the laboratory for evaluation. Six samples of the seal coat were usually taken from each project, three in the morning and three in the afternoon. A one gallon sample of the CRS-2 emulsion was taken from each of the tank delivery trucks; one gallon representing the morning seal coat specimen and another gallon representing the afternoon seal coat specimen. A sample of the mineral aggregate used on each project was taken from the stockpile at the job site.

Identification of Roads Studied

The identification of the seal coat road sections sampled in this research work are shown in Table I. The road projects are listed in order by route and section, district job number, county and date of

TABLE I

IDENTIFICATION OF SEAL COAT PROJECTS

No.	Route-Section	District Job No.	County	Location	Date Sampled
1	58-0	5-384	Izard	Guion-JCT 69	6-15-81
2	102-1	9-396	Benton	JCT 43-Decatur	8-12-81
3	95-2	8-120	Van Buren	Conway Co. Line-Scotland	6-25-81
4	348-2	4-355	Crawford	JCT 71-End of Maint.	7-1-81
5	7-13	8-125	Yell	Centerville-N & S	8-5-81
6	8-6	7-151	Dallas	JCT 7-JCT 9	7-8-81
7	21-4	9-400	Madison	Newton Co. Line-JCT 68	7-13-81
8	37-2	5-379	Jackson	Woodruff Co. Line-Amagon	7-14-81
9	82-2	7-154	Lafayette	Lewisville West-Stamps	7-22-81
10	31-1	2-237	Jefferson	JCT 15-North	7-27-81
11	35-3	6-147	Grant	JCT 167-Cleveland Co. Line	8-4-81
12	26-1	3-140	Howard	JCT 24-Pike Co. Line	8-1-81
13	49-9	1-447	Monroe	Phillips Co. Line-Brinkley	7-6-81
14	130-6	2-219	Arkansas	Stuttgart-Dewitt	7-15-71
15	1-14	1-450	Cross	Wynne-Vanndale	8-6-81
16	90-3	10-484	Clay	JCT 135-Green Co. Line	6-17-81
17	75-5	10-463	Poinsett	Crittenden Co. Line-JCT 63	7-16-81

sampling. The location of the seal coat sites are shown on the map of Arkansas in Figure 19.

The initial plan was to take samples representative of each emulsion manufacturer used in Arkansas during the 1981 sealing season. However, due to the bidding technique (weekly telephone bids) used, varying weather conditions, and construction equipment breakdown, the seal coat projects were sampled on a random basis from week to week. The first sample taken was on Route 58 on June 15, 1981 and the last sample was taken on Route 102 on August 12, 1981.

Field Data

The seal coat projects were constructed in a similar manner. Traffic was generally controlled by a lead vehicle as shown in Figure 20 using flagmen at each end of the work area. The pavement was swept with a power broom as shown in Figure 21. The seal coat samples were obtained by placing a sample plate in the center of the traffic lane as shown in Figure 22. The asphalt distributor applied the desired amount of emulsion as shown in Figure 23. A view of the emulsion coated sample is shown in Figure 24. The chip spreader followed the distributor and applied the prescribed amount of aggregate as shown in Figure 25. Usually two pneumatic rollers were used to embed the aggregate into the liquid asphalt emulsion. However, six of the seventeen test sections were also rolled with a steel wheel roller. Figure 26 shows the roller train in action. A view of the "hole" left in the seal coat after removal of the sample plate is shown in Figure 27.

About 500 gallons of CRS-2 emulsion was applied in one continuous pass. The chip spreader was stopped for reattaching the aggregate dump

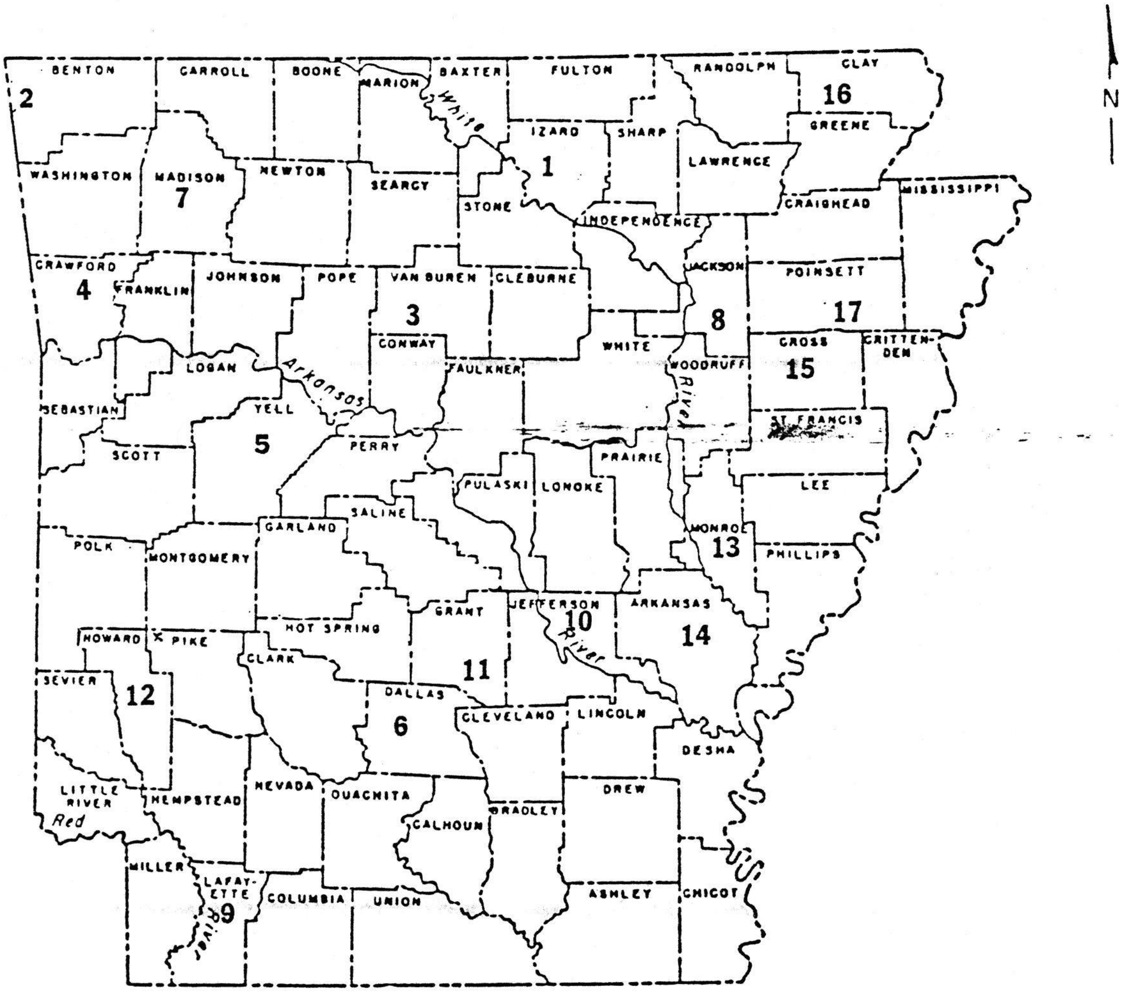


Figure 19. Location of the Seal Coat Projects

Figure 20. Traffic Control Using a Pilot Car

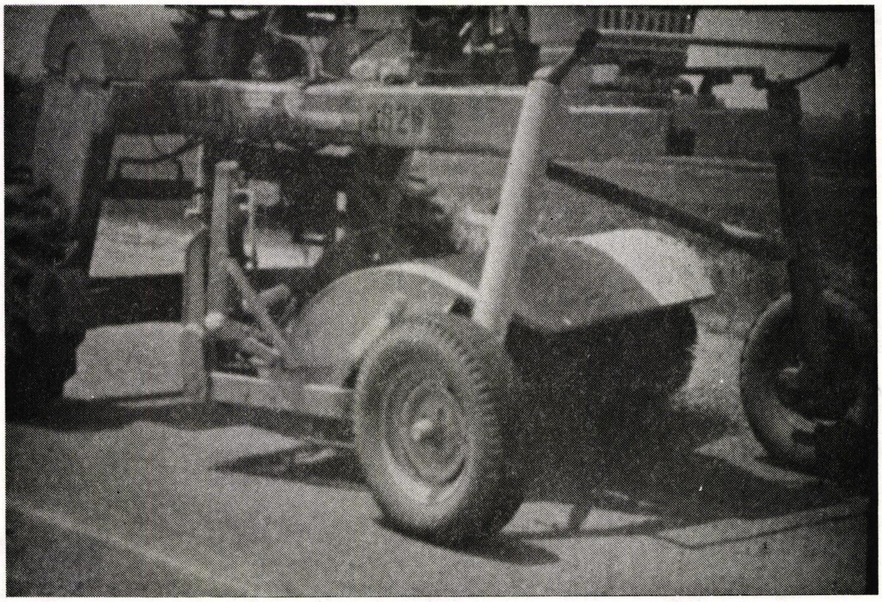


Figure 21. Power Broom Ahead of Distributor

Figure 22. Seal Coat Sample Plate Before Distributor Pass

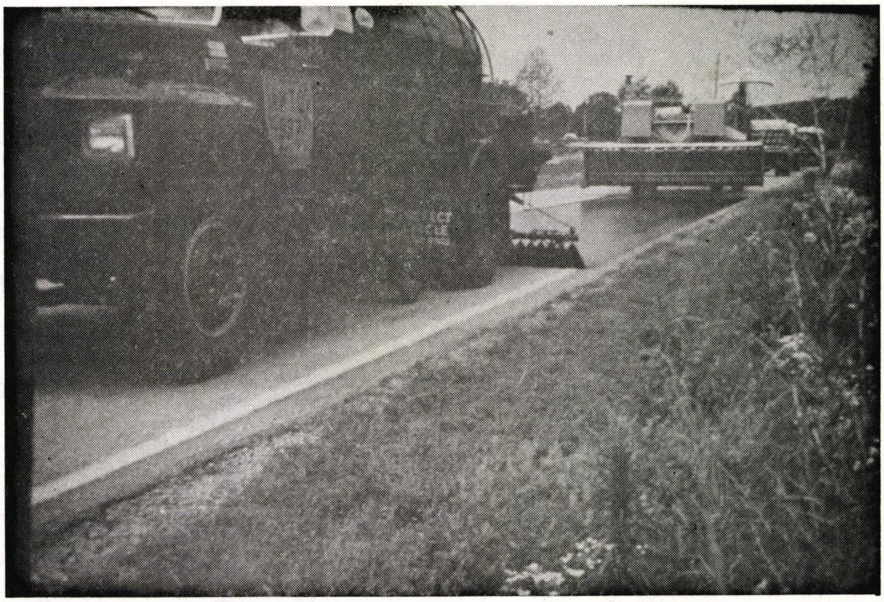


Figure 23. Distributor Spraying, Followed by Chip Spreader

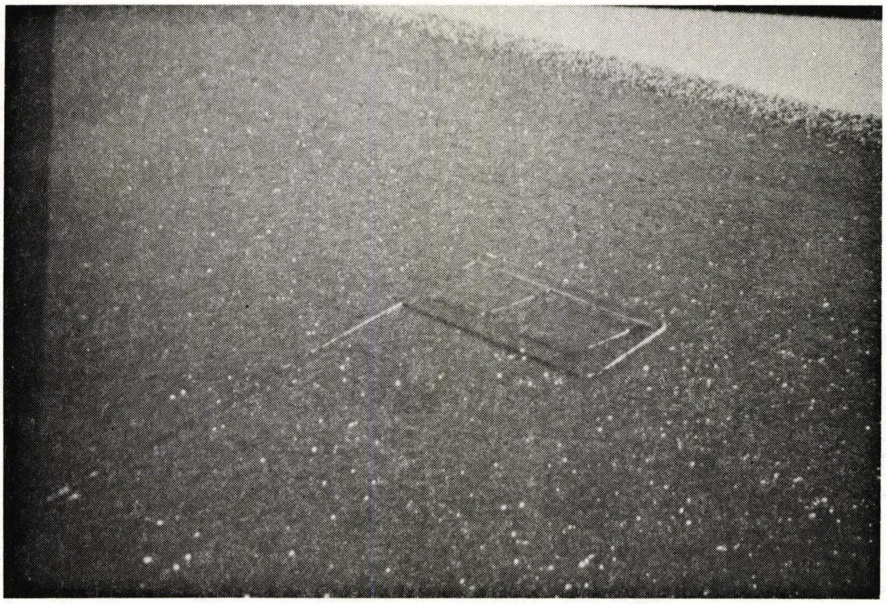


Figure 24. Sample Plate After Distributor Shot

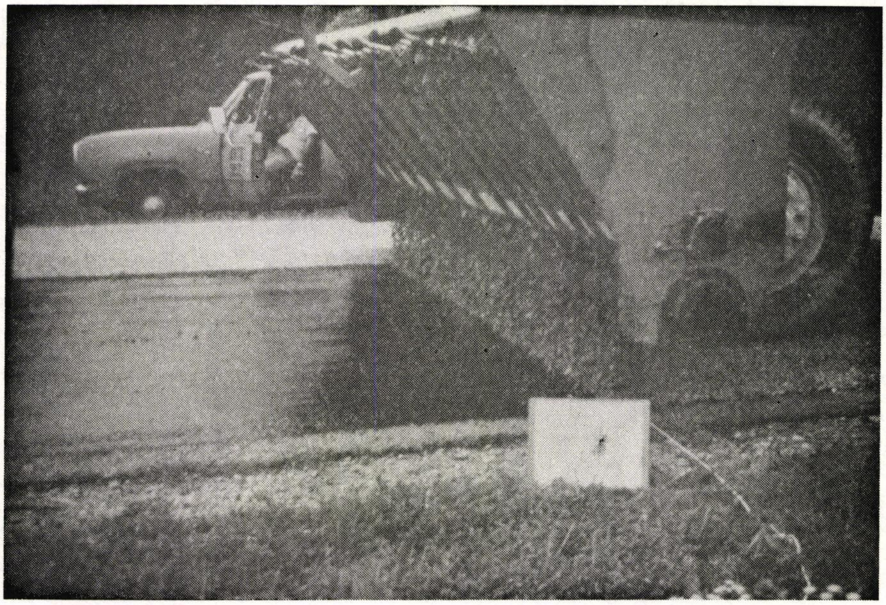


Figure 25. Chip Spreader About to Cover Sample Plate

Figure 26. Rollers Directly Behind Chip Spreader

Figure 27. Hole in Seal After Removal of Sample Plate

trucks as they were emptied. The rollers operated continuously, making a minimum of three passes over the fresh seal.

After refilling the distributor truck, the traffic then was shifted over to the freshly sealed pavement while the other lane was sealed. This procedure was repeated throughout the 10 hour work day of the maintenance sealing crew. An average of about 10,000 to 15,000 gallons of CRS-2 was applied during a typical sampling day.

Application Rates and 1981 Traffic

During the process of taking the seal coat samples the application rates of emulsion and aggregate were obtained from each job foreman. The "shot" quantities of CRS-2 emulsion and applied amount of aggregate for each job are shown in Table II. The 1981 ADT traffic for each sealing project is also shown in Table II.

The aggregate rate of application ranged from about 32 pounds per square yard (PSY) for the class 7 chip material to 14 PSY for the smaller SMA material. Emulsion application rates for the class 7 chips were about 0.50 gallon per square yard (GPY) while the SMA material required about 0.19 GPY of emulsion.

Traffic over the 17 sample sections ranged from 350 vpd on Route 8-6 in Dallas County to 6600 vpd on Route 82-2 in Lafayette County. The seal coats were applied over the existing pavements which had traffic lanes that varied from 10 to 12 feet wide.

Emulsion Source and Viscosity

The cationic emulsion samples taken from the seal coat projects were manufactured at seven different emulsion plants of five different

TABLE II

APPLICATION RATES AND 1981 TRAFFIC

No.	R-S	CRS-2	Aggregate	Traffic
		Gal/yd^2	lb/yd^2	ADT
1	58-0	0.50	27	450
2	102-1	0.45	32	410
3	95-2	0.49	26	510
4	348-2	0.40	30	1200
5	7-13	0.30	21	3100
6	8-6	0.37	30	350
7	21-4	0.40	21	690
8	37-2	0.31	21	560
9	82-2	0.37	30	6600
10	31-1	0.29	23	540
11	35-3	0.34	15	740
12	26-1	0.38	28	390
13	49-4	0.19	14	1500
14	130-6	0.19	14	1500
15	1-14	0.19	14	4200
16	90-3	0.19	14	800
17	75-5	0.22	14	750

manufacturers. Different methods of obtaining the CRS-2 sample from the tank delivery trucks were used. The gallon sample obtained for this study was taken at the same time that the AHTD record samples were taken. The record sample consisted of three (one gallon jugs) samples from each tank delivery truck.

The CRS-2 source for each job is given in Table III. For comparison purposes the AHTD Saybolt Viscosity test results are given for all of the samples tested for a particular seal job. These tests were performed within 24 hours of the time sampled. All of the samples complied with the AHTD specification limit of from 100 to 500 Saybolt seconds, except for Route 75-5 in Poinsett County. When available, the plant certification viscosity is also tabulated in Table III. Usually the plant viscosity was greater that the field viscosity.

The field CRS-2 samples were taken during the pumping process of emptying the tank delivery truck. A unique method was observed in the sampling process where a sampling device was installed on the delivery hose from the tank truck. This hose is shown attached to the delivery truck in Figure 28. A view of the sample device, a short section of pipe with a withdrawal valve, located at the end of the flexible transfer hose, is shown in Figure 29. The sample of CRS-2 was obtained, when desired, by opening the valve on the sample tube and filling the sample container during transfer of the emulsion from the tank delivery truck.

Aggregate Source and Description

The aggregate source, type and gradation used on the seal coat roads are shown in Table IV. The aggregates ranged in size from class 7

TABLE III
CRS-2 SOURCE AND VISCOSITY

No.	Route-Section	AHTD No. Tests	AHTD Saybolt (Seconds)	AHTD STD: DEV.	Plant Saybolt (Seconds)	CRS-2 Source (Location)
1	58-0	14	264	74	274	Bitucote (Jacksonville)
2	102-1	10	397	23	-	Riffe (Van Buren)
3	95-2	6	275	52	311	Riffe (Little Rock)
4	348-2	3	278	37	-	Riffe (Van Buren)
5	7-13	3	257	3	360	Bitucote (Jacksonville)
6	8-6	13	214	45	165	Bitucote (El Dorado)
7	21-4	12	257	53	-	Bitucote (Jacksonville)
8	37-2	10	265	47	-	Bitucote (Jacksonville)
9	82-2	4	235	13	-	Bitucote (El Dorado)
10	31-1	7	271	52	328	Chevron (Mobile)
11	35-3	7	233	34	-	Tosco (El Dorado)
12	26-1	11	240	30	-	Tosco (El Dorado)
13	49-9	2	394	-	466	Riffe (West Memphis)
14	130-6	10	228	28	-	Riffe (Little Rock)
15	1-14	2	316	-	323	Southern State (Memphis)
16	90-3	5	323	43	332	Riffe (West Memphis)
17	75-5	5	911	420	230	Riffe (West Memphis)

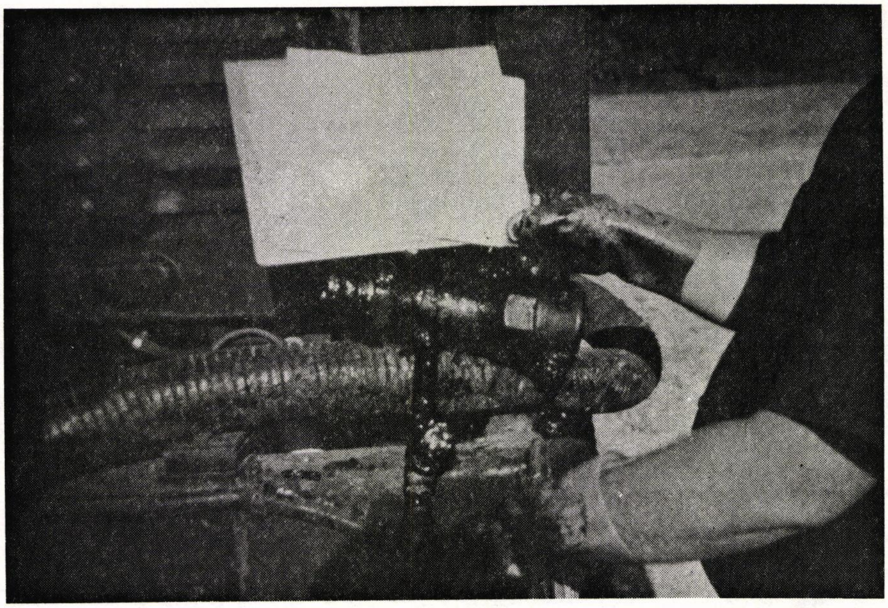


Figure 28. Sampling Device Used to Obtain Record Sample of Emulsion at Job Site

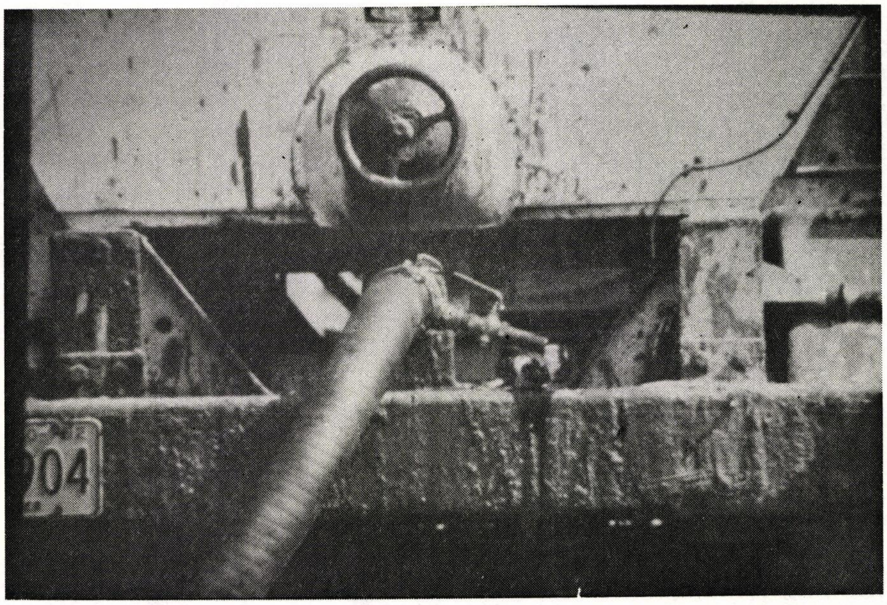


Figure 29. Sampling Device in Delivery Hose from Tank Truck to Obtain Emulsion Sample

TABLE IV

AGGREGATE IDENTIFICATION

No.	R-S	Source	Class	Type	AHTD Tests Minus #200 (%)	AHTD Tests Loose Wt. (pcf)
1	58-0	Black Rock	7	cr. limestone	N/A	89.9
2	102-1	Cherokee	10	cr. limestone	0.9	92.8
3	95-2	Treece	7	cr. sandstone	0.5	92.0
4	348-2	Van Buren	7	cr. sandstone	1.3	81.5
5	7-13	Duffield	10	cr. sandstone	0.8	97.0
6	8-6	Eagle Mills	8	pea gravel	1.0	94.3
7	21-4	Green Forest	8	creek gravel	1.3	102.4
8	37-2	Whitehall	10	pea gravel	0.2	91.2
9	82-2	Harrell	8	pea gravel	0.4	97.3
10	31-1	St. Francis	8	pea gravel	N/A	N/A
11	35-3	Hampton	10	pea gravel	0.7	80.0
12	26-1	Delight	10	pea gravel	0.1	98.9
13	49-9	N/A	SMA	cr. pea gravel	N/A	87.1
14	130-6	St. Francis	SMA	cr. pea gravel	N/A	N/A
15	1-14	N/A	SMA	cr. pea gravel	N/A	87.1
16	90-3	Black Rock	SMA	cr. limestone	0.3	N/A
17	75-5	St. Francis	SMA	cr. pea gravel	0.3	83.0

N/A = Not Available

(minus 3/4 inch) to special mineral aggregate (minus 3/8 inch). The aggregate samples include most of the different gradation and types of mineral aggregate used in Arkansas during the 1981 sealing season.

The aggregate source by quarry/pit name or supplier along with the general gradation class and type of material are given in Table IV. Six of the aggregates were crushed limestone or sandstone, six of the aggregates were pea gravel, four of the aggregates were crushed pea gravel, and one aggregate was a creek gravel.

The unit weight and minus No. 200 size material, as taken from AHTD records, are shown in the Table IV. The unit weights of the aggregate ranged from 80 to 102.4 pounds per cubic foot.

Construction Details

In general the seal coat jobs under study were constructed in a similar manner like that previously described. However, there were different factors involved with each job such as equipment, weather, pavement widths and type of aggregate. Each district sealing crew worked as a unit with each person doing their particular job well. The sequence of construction was orderly and the crews were very interested in obtaining a good seal coat. The major variations observed between district sealing crews included: a) number of distributors used, b) number of rollers used, c) the spraying temperature of the emulsion and d) the technique of applying the emulsion and aggregate. Some of these differences are as follows.

A self propelled chip spreader was used by each sealing crew. The gate opening and speed of the spreader was regulated to obtain the desired amount of aggregate coverage. However, the spreader used on

Route 348-2 had to be pushed by the haul trucks because the drive mechanism on the spreader was broken.

Two pneumatic rollers were used to embed the aggregate into the emulsion on most jobs. However, the number of roller passes over the field sample plates varied from three passes to as many as 12 or more passes. In fact, the greatest difference in the seal coat construction methods was in the rolling operation. The number and types of rollers used on each job are shown in Table V. The maximum rolling was on Route 58-0 where two pneumatic and two steel wheel rollers were used. Only one pneumatic roller was used on Route 348-2 and Route 7-13.

The spraying temperature of the emulsion was also observed to vary from job to job. The estimated spraying temperature for each job is shown in Table V. These temperatures were estimated to range from about 140 F to 180 F.

The aggregates used on all of the jobs were in a damp condition. Some of the aggregates were about saturated while others had surface moisture visible when placed on the road. No measurement of moisture content of the aggregate was made.

Condition Survey

A condition survey of the pavement surface before the new seal coat was applied was planned. This survey was to include a visual evaluation of the surface condition following the procedure detailed in NCHRP Project 10-9 report (35). In addition, the Mayes meter road roughness before sealing and after the first year of service was planned. Due to the random method of sampling the seal coat projects, there was not sufficient time to perform an initial condition survey of the study roads.

TABLE V

ROLLERS AND SPRAYING TEMPERATURES

No.	R-S	Pneumatic No.	Steel Wheel No.	Spraying Temperature * F
1	58-0	2	2	140^{-}
2	102-0	1	1	180^{+}
3	95-2	2	0	150
4	348-2	1	0	160
5	7-13	1	0	150
6	8-6	1	1	170
7	21-4	1	1	180^{+}
8	37-2	2	1	140^{-}
9	82-2	1	1	170
10	31-1	2	0	150
11	35-3	2	0	140^{-}
12	26-1	2	0	140^{-}
13	49-9	2	0	150
14	130-6	2	0	160
15	1-14	2	0	150
16	90-3	2	0	140^{-}
17	75-5	2	0	160

*Estimated

The evaluation of pavement condition of the seal coat roads after about eight months of service was performed by each District. However, no pavement roughness tests were performed on the study roads.

Miscellaneous Observations

The pea gravel used on Route 8-6 was visibly "dirty" and the clay coating on the peas soiled the aggregate sampling bag. Most of the other seal coat aggregates appeared to have been washed before delivery to the stockpile.

The pea gravel used on Route 26-1 was reported to sometimes give a good seal job and sometimes a bad seal job. This material was a mixture of dark colored peas and light colored peas. At the stockpile it was observed that a very light coating of fines would cover your hand when examining the damp peas. It was reported that these peas had a corrosive effect on the metal stitching on the chip spreader conveyer belt.

Several of the district sealing crew foremen expressed their opinion that a better seal coat would result if the chip spreader was not required to follow right behind the distributor truck, but should wait a short period of time before applying the chips. This delay procedure was followed in constructing the seal coats on Route 31-1, Route 75-5, Route 90-3 and Route 130-6. On the other seal coat projects under study the chip spreader followed the distributor truck very closely.

CHAPTER IV

TEST METHODS AND EQUIPMENT

The samples of aggregate, emulsion and seal coat specimen taken at the job site were returned to the laboratory for evaluation. Where possible, standard methods of test were followed in detemining the physical properties of the materials. The applicable ASTM methods of test followed for the aggregate, emulsion, and base asphalt samples are shown in Table VI.

Special test methods used for this work include: pH of emulsion, abrasion pH of aggregate, specific gravity, extraction and stripping of seal coat specimen, and accelerated wear or durability of seal coat specimen.

The circular wear track was modified for this research to accommodate twelve seal coat samples per test cycle. Approximately one week of test time was required to determine the relative durability of the field seal coat specimen using the procedure reported herein.

The test procedures that follow are grouped into areas by aggregate, emulsion and base asphalt, and seal coat field sample.

Aggregate

The aggregate taken from the stockpile was oven dried, quartered and tested to determine its characteristics. Standard tests performed include: sieve analysis (dry), specific gravity and absorption, minus No. 200 material, and unit weight.

The flakiness index test was performed in accordance with the procedures outlined in the Basic Asphalt Emulsion Manual (8). Particle sizes

TABLE VI

STANDARD TEST METHODS

No.	Test Method	ASTM(1)
1	Sieve Analysis of Fine and Coarse Aggregates	C-136-76
2	Specific Gravity and Absorption of Coarse Aggregate	C 127-77
3	Amount of Material Finer than No. 200 Sieve	C-117-76
4	Unit Weight of Aggregate	C 29-76
5	Emulsion Distillation	D 244-77
6	Penetration, Residue and Base Asphalt	D 5-73
7	Viscosity, Residue and Base Asphalt	D 2171-78
8	Softening, Residue and Base Asphalt	D 36-76
9	Ductility, Residue and Base Asphalt	D 113-79
10	Emulsion Coating Ability and Water Resistance	D 244-77
11	Extraction (by Reflux Extractor)	D 2172-75

(1) 1979 Annual ASTM Standards, Part 15 (33)

tested for flakiness were: 3/4 - 1/2 in., 1/2 - 3/8 in., 3/8 - 1/4 in., and 1/4 - 4. The combined flakiness index was calculated based upon the relative quantities of each particle size.

The abrasion pH of each aggregate was determined using a Fisher Accumet Model 610A pH Meter. The test procedure followed was based upon the report of Stevens and Carron (36). Their work reported a simple field test for distinguishing minerals by abrasion pH. The aggregate was prepared for test by sieving to size (1/2 to 3/8 in. or 3/8 to No. 4) and washing then oven drying the sample. About 1000 gram of the aggregate was placed into a stainless steel mixing bowl, 1000 ml of distilled water was added to the bowl and a Hobart Mixer with a stainless steel wire whip was used to stir the aggregate and water. A ten minute mixing time was used to abrade the aggregate particles in the mixing bowl. A sample of the water was withdrawn from the solution and the pH determined. This value is reported as the abrasion pH. The standard test method for pH of water, ASTM Designation D 1293-78 (routine pH determination of a batch sample), was followed.

Emulsion and Base Asphalt

The gallon samples of CRS-2 emulsion taken in the field were tested to determine their percentage residue, pH, coating ability and water resistance. The Saybolt viscosity of each sample was not determined in the laboratory because the samples had been in the jugs between three and five days in transport to the laboratory. The Saybolt viscosities of the AHTD record CRS-2 samples were obtained from each District Engineer and will be reported herein.

The asphalt residue from each emulsion distillation was tested for penetration, absolute viscosity, ring and ball softening point, and ductility. Likewise, the samples of base asphalt used in making the CRS-2 emulsions were tested for their penetration, absolute viscosity, ring and ball softening point, and ductility.

The pH of each emulsion sample was determined using the Fisher pH meter. About 50 ml of emulsion was taken from the top of the gallon jug and tested with the glass-body combination electrodes and the Fisher meter.

The coating ability and water resistance test of the CRS-2 emulsion with the job aggregate was performed. The procedure detailed in ASTM D244 was followed with the following changes: in lieu of the constant-head water spraying apparatus, the coated samples were washed with tap water dripping from a height of 12 inches; the job aggregates were washed, dried and sieved to pass a 3/8 in. sieve and be retained on a 1/4 in. sieve; and no calcium carbonate was used in the test. A 100 gram sample of prepared aggregate was prewetted with 2 grams of water and then 12 grams of CRS-2 was added to the mixing pan. The mixture was stirred by hand with a spatula for 5 minutes then divided into 2 parts. The control sample was placed on a white paper towel to dry and the remainder was washed with tap water until the overflow ran clear. The "stripped" sample was then placed on a towel to dry. The relative amount of uncoated surface was visually estimated.

Seal Coat Field Sample

The field samples of the seal coats were placed in a storage rack in the laboratory while awaiting tests. The samples were allowed to air dry (wrapped in paper) for about four months before any testing was initiated.

The aluminum plate which held the two trapezoidal asphalt impregnated sample plates had been assembled with the various pieces being tare weighted prior to being used to secure the emulsion and aggregate seal coat. The trapezoidal sample plates were cut from Onduline roofing panels. The size of the asphalt plates were such that 12 samples would fit on the circular wear track at one time. The area of the asphalt sample plate covered by the seal coat was about 34 sq. in.

Disassemble of Sample from Aluminum Plate

The asphalt plates were held to the aluminum plate with duct tape. The entire surface of the 1 ft. wide by 2 ft. long plate was covered with the seal coat sample. After removing the wrapping paper, the entire sample was weighed. Then the duct tape holding the asphalt plates was peeled back with a putty knife. The two trapezoidal plates were removed and weighed. The remainder of the asphalt and aggregate mix was scraped from the surface of the aluminum plate and placed into an enameled pan and weighed. The dimensions of the seal coat sample retained on the trapezoidal sample was determined by weighing in air and then in water. The weight and volume of each asphalt impregnated sample plate had been determined previously. The aluminum plate was cleaned and returned to the storage rack with the seal coated asphalt plates for the future test.

Extraction and Sieve Analysis

The mixture that was scrapped from the aluminum plate was tested for its asphalt content and gradation. The Rotarex method of extraction, using trichloroethane was used. No correction for ash content was made in this work. The dry weight of aggregate in the mix was determined by oven drying of the aggregate in the extraction bowl. The aggregate was then sieved using a Ro-Tap sieve shaker.

Using the asphalt content determined from the extraction test and the total weight of the asphalt mixture, the total weight of aggregate coverage and asphalt coverage was determined.

Panel Stripping Test

To estimate the effect of water on the seal coat specimens in the laboratory, a panel stripping test was devised. The test procedure was to weigh the air dry panel sample, then submerge it with aggregate side up in 77 F water for 18 hours, remove the sample from the water, invert it and recover any loose aggregate particles.

The loose aggregate was oven dried and weighed. Very little aggregate was loosened from the seal coat sample with the 77 F water temperature.

To simulate the effect of water on the seal coat in a summer rain, the sample was submerged in 130 F water for a period of one hour. Any loose rock was again removed from the specimen by inverting and brushing; the weight of the loosened material was determined after oven drying. The percentage weight loss of each job was calculated and will be reported as panel stripping.

Accelerated Wear Test

The effect of traffic on the durability of the seal coat specimen was determined using a circular wear track. The specimens were clamped to the top of the track, under the path of the wheels, using wood strips on the inside and outside edge of the panel. Twelve seal coat samples would fit on the wear track for each test cycle. A sketch of the wear track geometry is shown in Appendix A.

The axle on the wear track is rigid and may slide up and down on the drive shaft as the tires maintain a constant elevation for both wheels; opposing samples were identical so that each wheel passed over the same seal coat sample at the same time. Thus a total of six diferent seal coat samples were tested in the accelerated wear device (AWD) at one time. To prevent bumping as the tire passed over one sample to the next, the samples were chosen to have approximately equal thickness or heights, based on the sieve analysis of the extracted mixture.

The AWD was operated to cause the rubber tires to roll over the seal coat specimen to simulate the effect of traffic. The operating temperatures and wheel passes were chosen to cause wear of the seal coat specimens. This wear was taken to be equal to the loss in weight of each specimen as the tires dislodged and remove the seal coat materials. E. J. Baker, Jr. (37) reported the development of the accelerated durability test equipment and test procedure that was used to evaluate all of the field seal coat specimens.

The actual test cycles and temperatures used for the accelerated wear test are shown in Table VII. To prevent excess pickup or plucking out of the aggregate particles from the asphalt matrix by the rubber tires, especially at summer temperatures, a bond breaker was applied to the surface of the tires. This bond breaker was a very light coating of liquid soap which was used as needed to prevent pickup.

At the end of each temperature-wear cycle, the samples were removed from the AWD and weighed. The loose material on the wear track was then removed and the samples reclamped to the table for continued testing. A set of six seal coat job specimens required about 10 laboratory days to accomplish the 30,000 wheel passes on the circular wear track. The field samples lost between 15 and 50 percent of their material using the temperatures and wheel passes shown in Table VII.

Extended tests, up to 80,000 wheel passes, were used on the more durable seal coat specimens to determine their relative performance. As a matter of fact the AWD was a comparative test, all samples being subjected to the action of the rubber tire (20 psi pressure) as it revolved on the 14 inch radius axle at 20 revolutions per minute.

The AWD tires were maintained at 20 psi, the total weight of the axle assembly was 126 pounds. The nylon tires were 11X6.0-5, 2 ply rating, go-cart "super slicks". The tires revolved on the 14 inch radius axle at 20 revolutions per minute. The temperature of the surface of the wear track was maintained using four heat lamps suspended over the top of the track; cooling was provided by chill water lines clamped under the 0.5 inch steel track along the center line of the circular track.

TABLE VII

ACCELERATED WEAR DEVICE TEST

TEMPERATURES AND WHEEL PASSES

Cycle No.	Surface Temperature ~F	Number Wheel Passes	Accumulated Wheel Passes
1	72	600	(initial "shake down")
2	72	1,400	2,000
3	93	2,000	4,000
4	54	6,000	10,000
5	72	10,000	20,000
6	92	4,000	24,000
7	72	6,000	30,000

CHAPTER V

TEST RESULTS AND DISCUSSION

The information obtained from laboratory tests, field observations and regression analysis is reported in this chapter. The order of data presentation is: aggregate, emulsion and base asphalt, seal coat, and correlation. The data tabulated are the average of those test values obtained for each seal coat job. The average test values were also used in preparing the graphical relationships in most instances. In some cases the specific (single) test result has been used for comparisons between different seal coat samples.

Aggregate Tests

The source of the aggregate material was the sample taken at the stock pile and the extracted aggregate sample from each individual test panel. Usually six test panels were obtained on each job. However, only three test panels were taken on Route 35-3 and four test panels were taken on Route 1-14.

The gradation of the aggregate samples for each job are given in Table VIII. The stockpile sample gradation was obtained from AHTD tests, while the extracted gradations are the average value obtained from the seal coat panel specimens.

All of the aggregate gradations were plotted on a semilog grading chart and compared with the Arkansas State Highway and Transportation Department specifications for mineral aggregate to be used in bituminous surface courses (38, 39). The specification grading limits for the various classes of aggregate are shown in Table IX.

TABLE VIII

Aggregate Gradation - Stockpile and Inplace Samples

No.	R-S	SOURCE / Sieve Size	TOTAL PERCENT PASSING 3/4"	1/2"	3/8"	#4	#10	#16	#40
1	58-0	AHTD	100	96.3	-	8.1	1.7	-	-
		extraction	100	97.7	76.8	16.5	4.6	3.0	1.7
2	102-1	AHTD	100	94.8	59.6	4.1	2.1	1.8	-
		extraction	100	99.3	87.6	39.4	17.3	12.0	7.4
3	95-2	AHTD	100	95.6	77.1	11.0	0.8	-	-
		extraction	100	95.8	70.3	15.0	3.7	2.4	1.7
4	348-2	AHTD	100	92.4	56.5	5.0	2.9	-	-
		extraction	100	92.4	60.8	12.2	4.7	3.5	2.8
5	7-13	AHTD	100	99.8	81.6	6.8	2.0	0.8	-
		extraction	100	100	94.5	29.9	7.3	4.9	3.5
6	8-6	AHTD	100	100	100	51.0	4.0	2.0	-
		extraction	100	100	99.9	57.8	8.8	5.3	3.2
7	21-4	AHTD	100	95.7	67.2	4.4	2.5	2.2	-
		extraction	100	100	99.4	39.2	11.2	5.7	2.6
8	37-2	AHTD	100	99.0	-	16.0	2.0	1.0	-
		extraction	100	100	99.5	24.3	3.8	2.6	1.3

TABLE VIII (CONCLUDED)

No.	R-S	SOURCE Sieve Size	TOTAL PERCENT PASSING 3/4"	1/2"	3/8"	#4	#10	#16	#40
9	82-2	AHTD	100	100	100	37.0	2.0	1.0	-
		extraction	100	100	99.4	33.2	4.3	2.8	1.8
10	31-1	AHTD	100	100	99.7	46.0	3.0	1.0	-
		extraction	100	100	99.6	50.8	6.2	2.4	1.2
11	35-3	AHTD	100	100	100	28.6	2.0	1.3	-
		extraction	100	100	99.6	31.1	3.2	1.9	1.3
12	26-1	AHTD	100	100	98.0	27.0	2.3	1.3	-
		extraction	100	100	97.1	24.4	2.3	1.1	0.6
13	49-9	AHTD	100	100	100	48.0	10.0	6.0	-
		extraction	100	100	100	60.6	15.2	8.5	3.5
14	130-6	AHTD	100	100	99.9	44.0	8.0	5.5	-
		extraction	100	100	99.3	44.5	8.9	5.2	2.4
15	1-14	AHTD	100	100	100	48.0	10.0	6.0	-
		extraction	100	100	100	55.5	9.6	5.2	2.2
16	90-3	AHTD	100	100	100	78.2	2.1	0.7	-
		extraction	100	100	100	82.8	5.6	1.7	-
17	75-5	AHTD	100	100	100	66.8	3.9	1.1	-
		extraction	100	100	100	71.2	7.9	2.7	0.9

TABLE IX

ARKANSAS STATE HIGHWAY AND TRANSPORTATION DEPARTMENT SPECIFICATION LIMITS (38, 39)

Sieve Size	Total Percent Passing		
	Class 7	Class 8	SMA
3/4"	100	-	-
1/2"	90-100	100	-
3/8"	-	90-100	100
No. 4	0-15	-	40-90
No. 10	0-3	0-15	0-20
No. 16	-	0-3	0-10

The extracted aggregate sieve analysis reflects only the aggregate particles which were attached to the asphalt binder on the sample plate. None of the crushed stone materials met the specification for class 7 or class 8 material. Only the pea gravel of Route 31-1 met the specifications for a class 8 material. The pea gravel used on Route 8-6 and Route 21-4 met the grading specification for an SMA material except for having a small amount of material retained on the 3/8 inch sieve.

Extracted aggregate gradings are shown on Figure 30 for Route 58-0 and Route 7-13 along with the AHTD grading limits for a class 7 material. The materials for both jobs were too fine to meet the class 7 limits. Figure 31 presents the grading limits for a class 8 material and the gradations for Route 35-3 and Route 26-1. It is noted that the materials were too coarse to meet the grading of a class 8 material. Examination of the gradations of Table VIII for Routes: 58-0, 102-1, 95-2, 348-2, 7-13, 8-6, 21-4, 37-2, 82-2, 35-3 and 26-1 indicate that they generally fall between the grading limits of a class 7 and a class 8 material.

Extracted aggregate gradings for Route 49-9 and Route 75-5 are shown in Figure 32. The grading limits for an SMA material are also shown on Figure 32. The crushed gravel used on Routes: 49-9, 130-6, 1-14 and 75-5 met the grading limits for a SMA material. The crushed limestone for Route 90-3 also met the SMA grading limits.

Results of physical tests performed on the aggregates for all 17 jobs are shown in Table X. The average grain size (P50) was taken to be the size at the 50 percent line on the grading chart. The P50 grain size ranged from 0.30 inch on Route 348-2 to 0.14 inch on Route 90-3. The spread modulus, M, was calculated using the equation taken from the

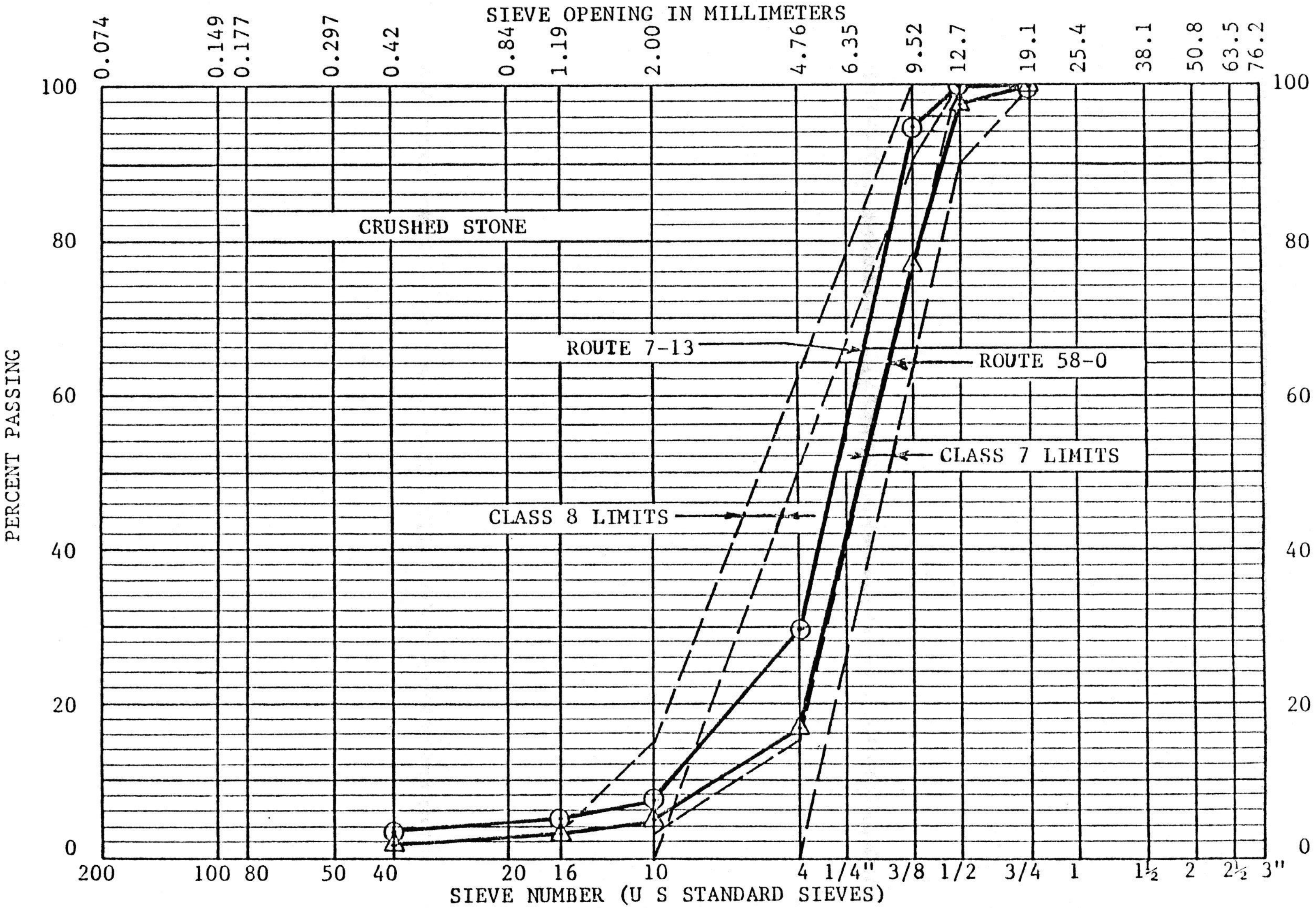


Figure 30. Extracted Aggregate Gradings, Route 58-0 and Route 7-13 with AHTD Class 7 Grading Limits

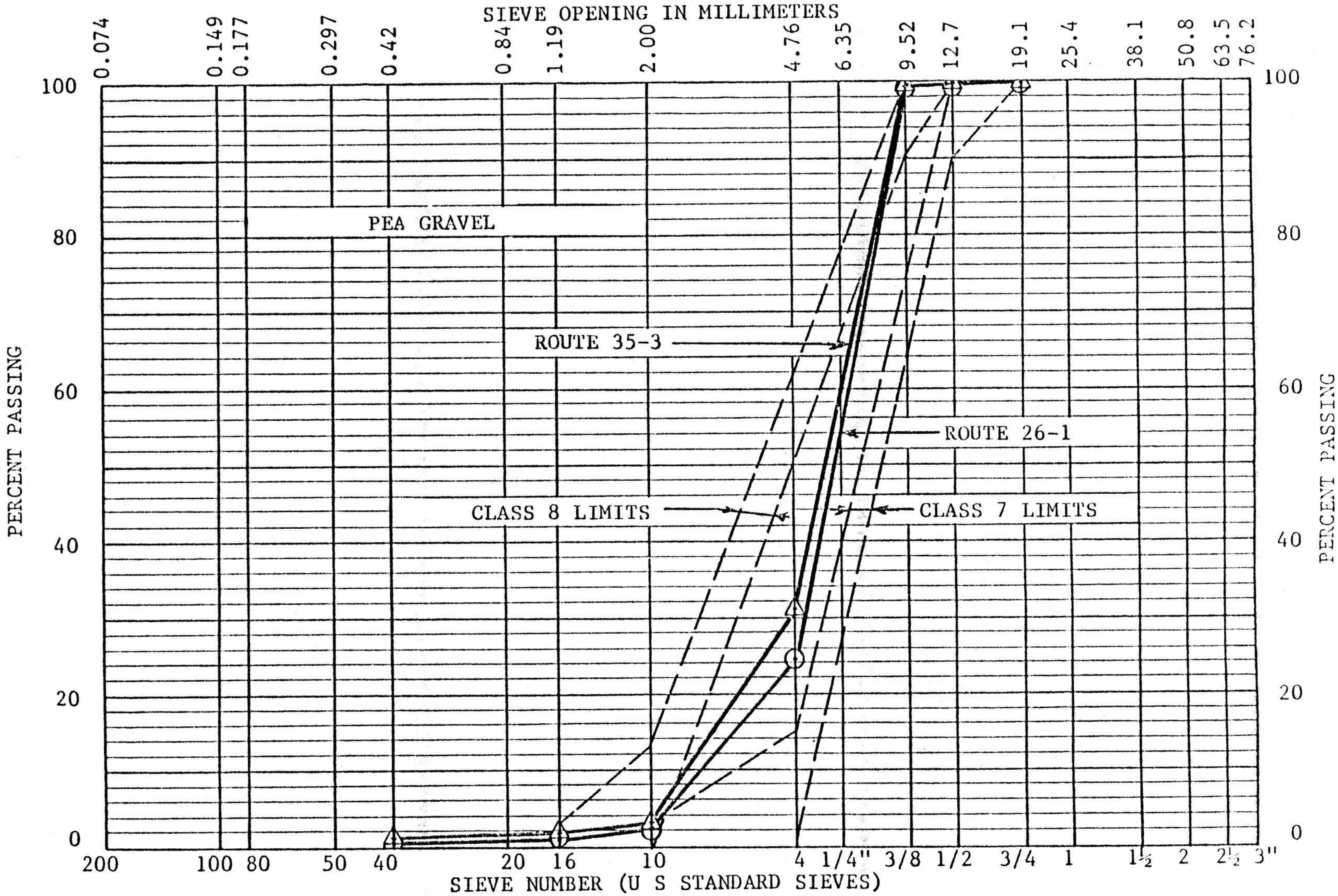


Figure 31. Extracted Aggregate Gradings, Route 35-3 and Route 26-1 with AHTD Class 8 Grading Limits

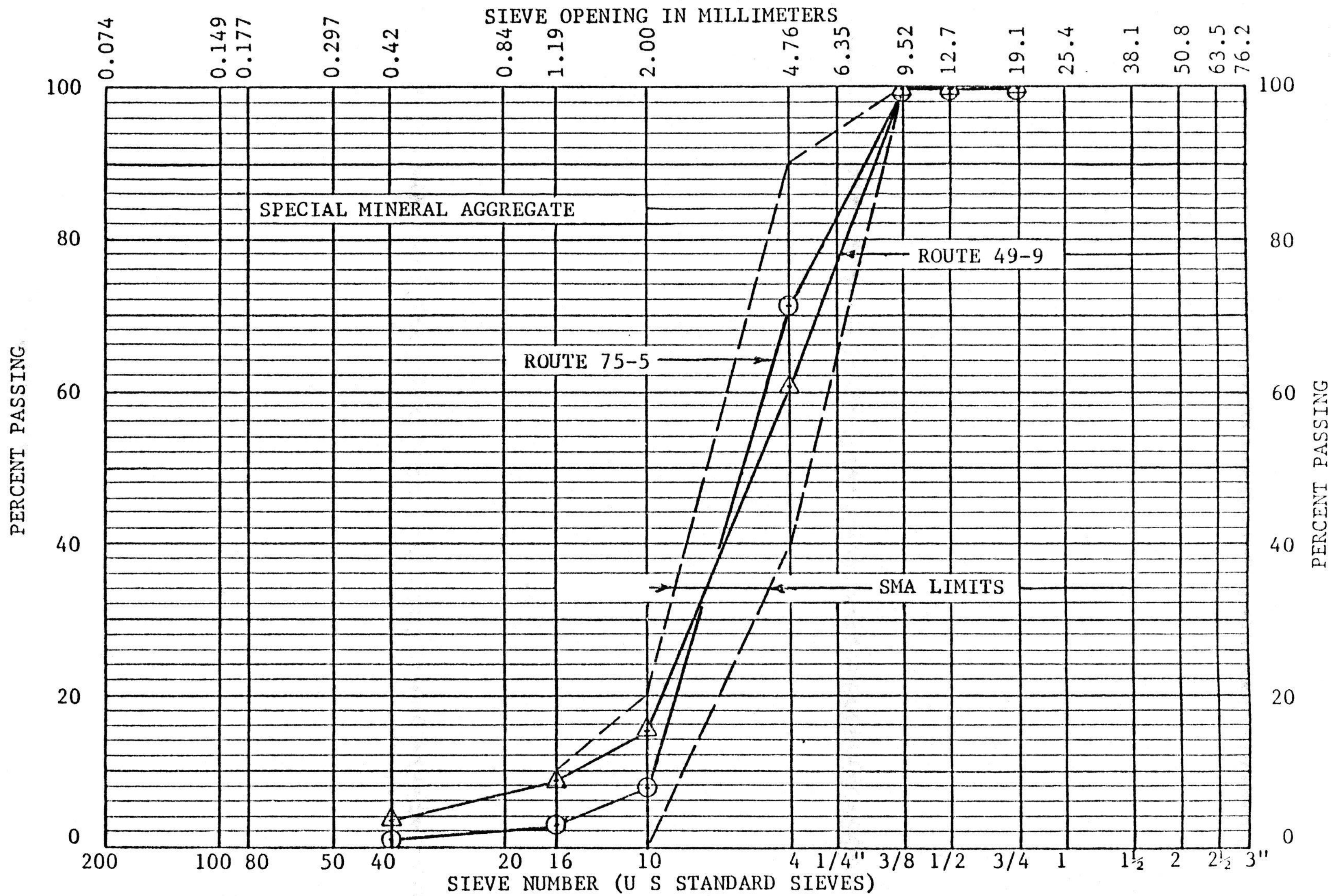


Figure 32. Extracted Aggregate Gradings, Route 49-9 and Route 75-5 with AHTD Special Mineral Aggregate Grading Limits

TABLE X

AGGREGATE PHYSICAL PROPERTIES

No.	R-S	Average Size-in.	Spread Modulus, in.	Minus #200-%	Bulk Sp. Gravity	Flakiness Index	Avg.Least Dim.-in.	Abrasion pH
1	58-0	0.28	0.31	3.3	2.681	39.5	0.18	9.1
2	102-1	0.24	0.25	1.8	2.534	38.7	0.15	8.4
3	95-2	0.29	0.30	3.6	2.608	26.0	0.21	8.1
4	348-2	0.30	0.33	2.4	2.491	37.2	0.19	8.1
5	7-13	0.23	0.24	3.1	2.592	33.2	0.16	7.6
6	8-6	0.16	0.19	1.2	2.485	25.7	0.11	6.5
7	21-4	0.22	0.21	0.1	2.309	23.7	0.16	8.0
8	37-2	0.24	0.23	0.2	2.546	18.6	0.18	7.8
9	82-2	0.22	0.22	0.6	2.543	18.2	0.16	5.7
10	31-1	0.18	0.20	0.4	2.511	17.3	0.13	5.9
11	35-3	0.23	0.23	0.5	2.544	19.3	0.17	5.5
12	26-1	0.24	0.24	0.4	2.541	13.8	0.19	5.9
13	49-9	0.16	0.18	1.4	2.536	29.0	0.13	7.5
14	130-6	0.22	0.21	0.8	2.577	19.6	0.16	6.7
15	1-14	0.17	0.19	0.8	2.531	10.5	0.12	7.7
16	90-3	0.14	0.18	0.5	2.704	9.0	0.10	9.1
17	75-5	0.19	0.20	0.1	2.515	23.3	0.14	7.4

Asphalt Institute Manual Series No. 13 (40). This value may be used to estimate an average particle size of a graded aggregate and is based on the aggregate gradation. In general, the M value was 0.01 to 0.04 inches greater than the P50 grain size.

The average least dimension (ALD) for each seal coat was determined using the P50 grain size and the flakiness index in accordance with the procedures and curves in the Basic Asphalt Emulsion Manual (8). These values of ALD are shown in Table X. The average ALD for the crushed stone (class 7) chips was about one-third less than the P50 grain size. The average ALD for the class 8 peas and SMA materials was about one-fourth less than their P50 grain size.

The minus #200 material reported in Table X was obtained from washing the material sampled from the stockpile. Of interest is that the crushed stone materials indicated greater than 1.5 percent minus #200 material for all 5 jobs. Also, it is interesting to note that the "dirty" peas on Route 8-6 only had 1.2 percent material finer than a #200 sieve. All of the other jobs had minus #200 material ranging from 0.1 to 1.4 percent.

The flakiness index (FI) was calculated based upon the sieve analysis of the extracted materials. The FI ranged from 9.0 on Route 90-3 to a high of 39.5 on Route 102-1. No significant relationships of FI with other factors was established.

The abrasion pH of each aggregate is reported in Table X. The highest pH of 9.1 was measured on the limestone from Routes 58-0 and 90-3; both materials were from the Black Rock quarry. The crushed stone materials were all basic, with a pH greater than 7.0; the pea gravels usually had a pH of less than 7.0. It is noted that the gravels on

Routes 21-4, 37-2, 49-9, 1-14 and 75-5 had pH's greater than 7.0. Possibly there could have been some soft calcareous particles in the aggregate stockpile samples to cause the abrasion pH water to become basic.

Emulsion and Base Asphalt Tests

The samples of CRS-2 taken in the one gallon jugs were tested for their percentage residue and pH. The base asphalt and the residue from the distillation test were tested for penetration, absolute viscosity, softening point and ductility. The ductilities of the residual asphalt and base asphalt were greater than 100 cm at 77 F.

CRS-2 Tests

The CRS-2 test results are shown in Table XI. All Saybolt viscosity test values are the results of tests performed in each AHTD district laboratory. The Saybolt viscosity ranged from 171 seconds to 394 seconds on 16 of the jobs. For Route 75-5, the Saybolt viscosity was 950 seconds at 122 F. When this sample was retested at 160 F, a Saybolt viscosity of 550 seconds was obtained, which was out of specifications.

The residue from distillation ranged from 68.0 percent to 71.1 percent. The percentage residue and Saybolt viscosity was compared with the typical emulsion as shown in Figure 1; all of the data points of Table XI were to the right of this typical curve. The pH of the emulsion was acidic and varied from 2.0 to 3.5. The relationship between pH and percentage residue is shown in Figure 33. The linear best fitted curve had a coefficient of correlation (R) of 0.53, and indicates a decrease in pH as the amount of residue increases.

TABLE XI

CRS-2 PHYSICAL PROPERTIES

No.	R-S	Saybolt Viscosity Seconds(1)	Distillation Residue %	pH	Penetration 77F, 100g 5 seconds	Softening Point °F	Viscosity 140°F Poises
1	58-0	257	68.7	2.0	103	114	1120
2	102-1	380	68.2	2.8	122	110	1290
3	95-2	326	68.0	2.4	118	114	1200
4	348-2	304	69.2	3.4	124	114	1000
5	7-13	255	69.7	2.2	107	112	1070
6	8-6	171	69.5	3.3	109	114	990
7	21-4	248	68.0	2.2	101	115	1130
8	37-2	282	68.0	2.2	107	115	1200
9	82-2	239	69.1	3.2	113	115	960
10	31-1	312	69.9	2.8	142	110	820
11	35-3	268	71.1	3.4	122	112	870
12	26-1	230	70.5	3.4	127	110	870
13	49-9	394	68.6	2.9	108	114	1110
14	130-6	228	69.8	3.0	116	112	1120
15	1-14	316	70.6	3.5	166	106	455
16	90-3	246	68.0	3.5	121	109	540
17	75-5	950	68.5	2.5	134	116	1110

(1) From AHTD Tests

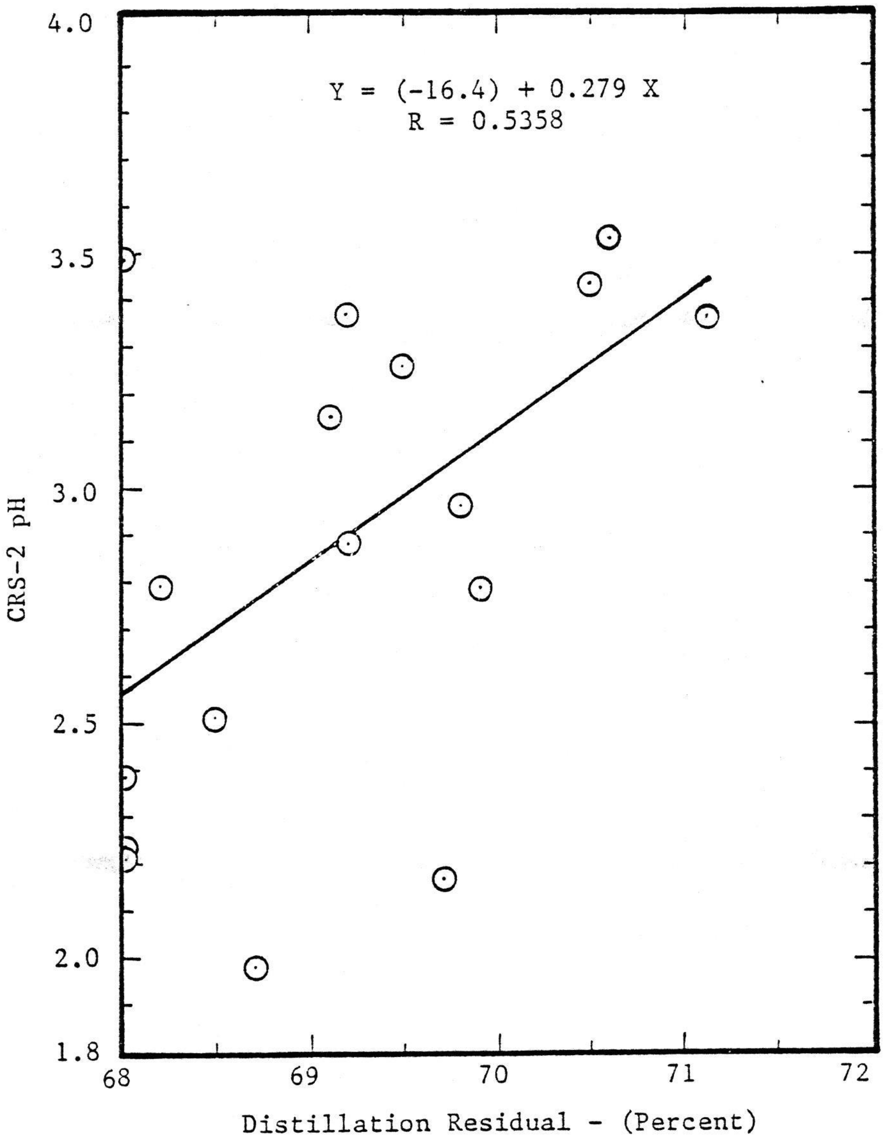


Figure 33. Relationship Between CRS-2 pH and Percentage Asphalt Residue

The CRS-2 residual penetrations varied from 101 to 166 while the absolute viscosities ranged from 455 poises to 1290 poises. Figure 34 shows the relationship between penetration and viscosity, with the viscosity decreasing as the penetration increases. By regression analysis the best fitted equation for this data is:

$$\text{Ln Viscosity} = 8.30 - 0.119 \text{ Penetration}$$

and has the form of natural logarithm versus linear. The R value was 0.68, which indicates a fairly good correlation.

The softening point of each CRS-2 residual asphalt is shown in Table XI. The softening points ranged from 106 F to 115 F. The softening point and penetration values may be used to calculate the penetration temperature susceptibility factor (PTS) and the penetration index (PI) of the asphalt. The PTS factor and PI were calculated for each job; however, they are not reported herein as they had no significant relationships with other variables.

From the test data presented in Table XI it appears that the asphalt recovered by distillation of the emulsions may be classified as a viscosity grade AC-10 with but two exceptions. These are Route 1-14 and Route 90-3, for which the asphalt used was an AC-5. The emulsion test data presented in Table XI indicates that the sampled materials meet the requirements for a CRS-2 emulsified asphalt except as previously noted.

Base Asphalt Tests

Samples of the base asphalt used in manufacturing the CRS-2 emulsion were obtained on 14 of the different jobs. Base asphalt samples were not obtained on Routes 31-1, 35-3, and 1-14. The base asphalt used with the Tosco emulsion on Route 35-3 was reported to be a Tosco AC-10

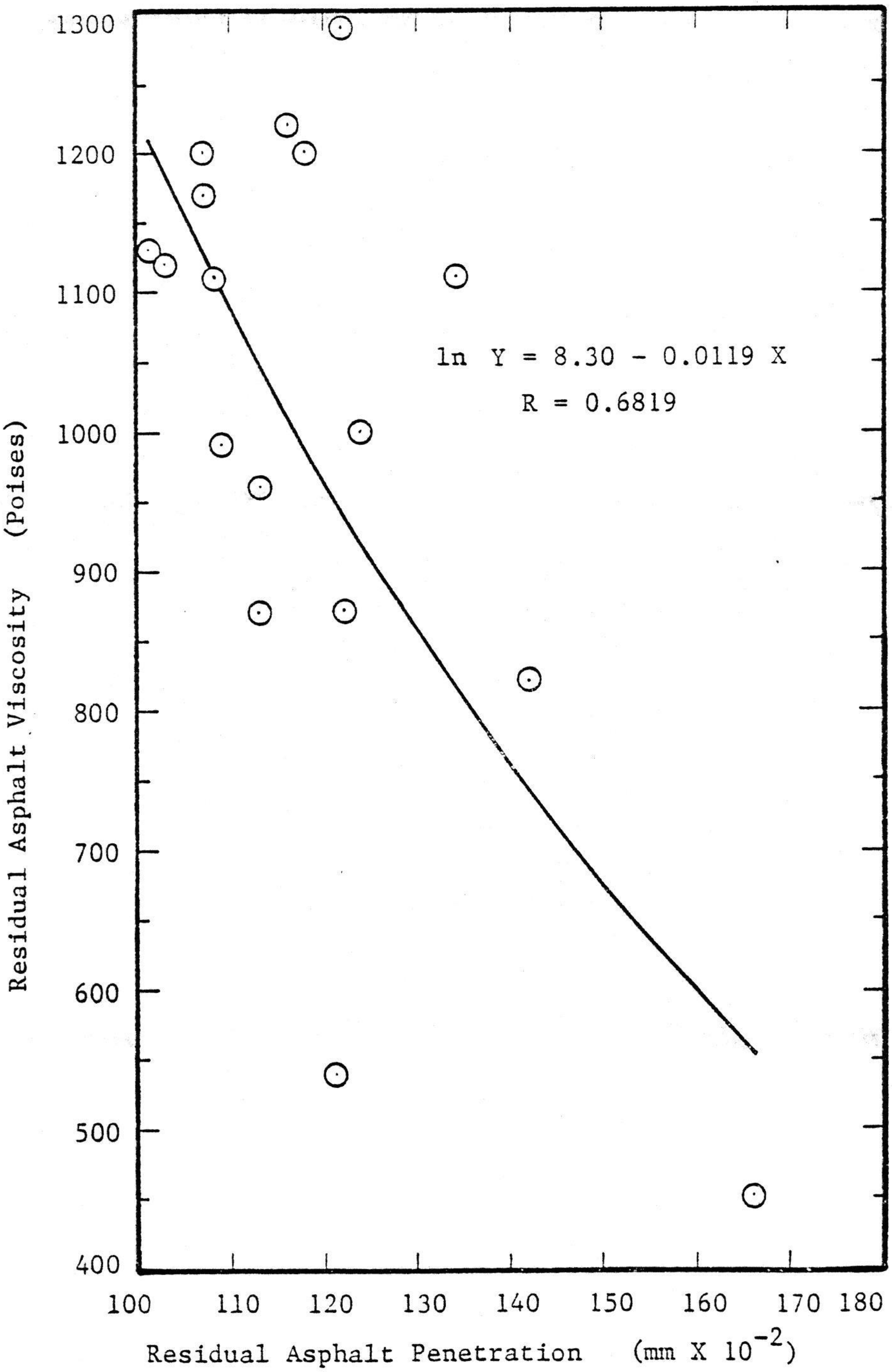


Figure 34. Relationship Between Viscosity and Penetration of Residual Asphalt

asphalt. The other emulsions were manufactured out of state. It is noted that the same base asphalt cement was used to manufacture the emulsion used on Route 49-9 and Route 75-5.

The results of the laboratory test on the base asphalts are shown in Table XII. The softening points of the base asphalt averaged 110 F, while the softening points of their CRS-2 asphalt residue averaged 112 F. This indicates no appreciable change in the softening point due to emulsification, with an average increase of 2 F. As before, the penetration temperature susceptibility factor and penetration index for each asphalt sample was determined. Again, there was no significant relationships of PTS or PI with other measured variables.

The average penetration and absolute viscosity of the base asphalt were, respectively, 118 and 910 poises. Based on the viscosity test results, all of the base asphalt cement may be classified as a viscosity graded AC-10 except for Route 90-3, which appears to be an AC-5 asphalt. On the average, the penetration of the base asphalt increased very little due to emulsification. The absolute viscosity of the base asphalt increased from 910 poises to 1000 poises on the average of the samples tested.

The relationship between penetration of the residual asphalt versus the penetration of the base asphalt is shown in Figure 35. The best fitted equation was of the form logarithm residual penetration versus logarithm of the base asphalt, having an R value of 0.49. As can be seen from the graph, this correlation indicates a rather large scatter of the data points from the best fitted curve drawn on Figure 35.

The relationship between absolute viscosities of the residual asphalt and base asphalt are shown in Figure 36. The best fitted

TABLE XII

BASE ASPHALT PROPERTIES

No.	R-S (1)	Penetration 77F, 100g 5 seconds	Softening Point ^{o}F	Viscosity 140F Poises
1	58-0	112	110	890
2	102-1	112	112	1270
3	95-2	120	110	950
4	348-2	150	106	880
5	7-13	110	110	950
6	8-6	117	109	880
7	21-4	112	112	890
8	37-2	101	111	990
9	82-2	115	108	820
12	26-1	113	110	840
13	49-9	119	111	950
14	130-6	116	112	1060
16	90-3	131	111	420
17	75-5	119	111	950

(1) No. 10 (31-1), No. 11 (35-3) and No. 15 (1-14) were not sampled.

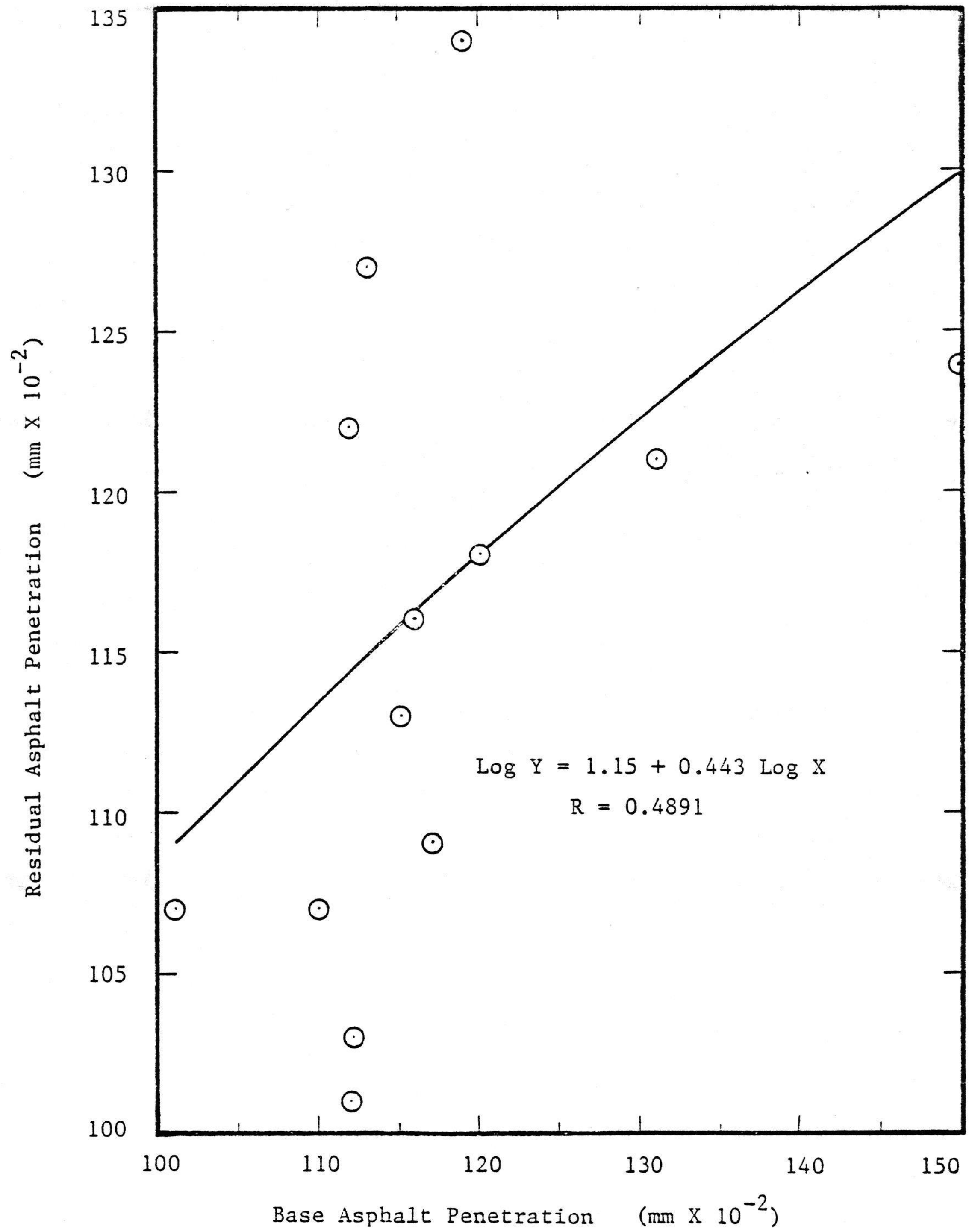


Figure 35. Relationship Between Penetration of the Residual and Base Asphalts

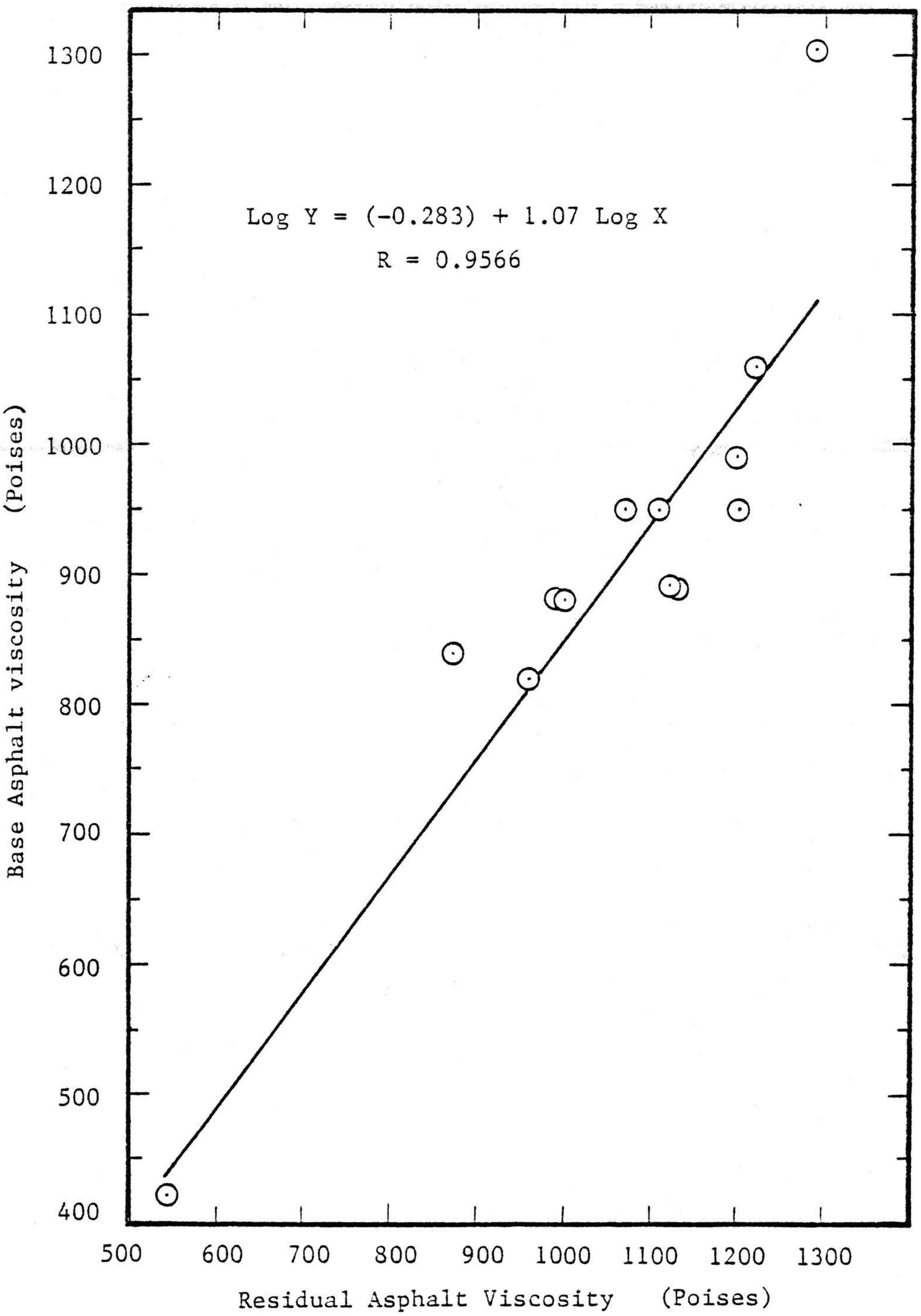


Figure 36. Relationship Between the Absolute Viscosities (140F) of the Residual and Base Asphalts

equation for this data was of the form log-log and has an R value of 0.96. This indicates a very good relationship between the viscosities of the base asphalt cement and the CRS-2 residual asphalt, as may be seen on Figure 36.

Seal Coat Tests

The seal coat samples were evaluated for their individual physical characteristics including: amount of residual asphalt and aggregate, percentage asphalt content, panel bulk specific gravity and mat thickness. This data plus the AWD durability data will follow.

Application Rates

The total amount of aggregate and asphalt contained on each sample plate was determined by weight. The accelerated wear device trapezoidal specimens were contained on an asphalt impregnated fiber material. This material approximated an existing bituminous pavement surface. The asphalt absorption of this sample plate was assumed to be zero. The asphalt and attached aggregate on the other portions of the aluminum plate were removed and extraction tests were performed to determine the amount of asphalt. The percentage of asphalt (based on weight of asphalt and aggregate) is reported in Table XIII. These asphalt contents ranged from 6.8 percent to 13.3 percent for the 17 seal coat jobs.

The application rates of aggregate and asphalt were calculated based upon the extraction test data. The amount of aggregate on the seal coat jobs ranged from a low of 8.7 lbs. per square yard (PSY) on Route 49-9 to a high of 22 PSY on Route 58-0. The residual asphalt cement was assumed to have a specific gravity of 1.02 in order to calculate its

TABLE XIII

SEAL COAT PHYSICAL PROPERTIES

No.	R-S	Residual Material			Seal Coat Bulk Sp. Gravity	Mat Thick. - (in.)	
		Asphalt gal/yd^2	Aggregate lb/yd^2	(Extraction) % Asphalt		Before AWD	After AWD
1	58-0	0.23	22	8.0	2.304	0.34	0.30
2	102-1	0.30	21	10.9	2.088	0.33	0.28
3	95-2	0.20	17	8.9	2.314	0.35	0.30
4	348-2	0.26	18	10.9	2.243	0.43	0.31
5	7-13	0.21	13	12.1	2.186	0.32	0.22
6	8-6	0.18	18	7.9	2.060	0.31	0.24
7	21-4	0.21	17	9.7	1.976	0.29	0.26
8	37-2	0.16	16	8.3	2.108	0.29	0.24
9	82-2	0.22	20	8.6	2.028	0.30	0.20
10	31-1	0.19	15	9.6	2.111	0.26	0.20
11	35-3	0.23	17	10.5	2.008	0.27	0.24
12	26-1	0.18	21	6.8	2.163	0.37	0.20
13	49-9	0.16	8.7	13.3	2.025	0.18	0.12
14	130-6	0.12	9.0	10.6	2.234	0.27	0.22
15	1-14	0.13	11	9.4	2.111	0.18	0.12
16	90-3	0.12	9.7	9.8	2.411	0.17	0.11
17	75-5	0.14	10	10.8	2.088	0.19	0.14

volume. The amount of asphalt coverage ranged from 0.12 gallons per square yard (GSY) on Route 90-3 to 0.30 GSY on Route 102-1.

Seal Coat Specific Gravity and Thickness

Each trapezoidal seal coat sample was weighed in air then submerged in water and weighed as quickly as possible. The bulk specific gravity of the seal coat was then calculated. Their specific gravities ranged from 1.976 to 2.411 as shown in Table XIII. The mat thickness was estimated by random measurement of the seal coat specimen before and after testing on the AWD. The seal coat thickness varied from 0.17 inch to 0.43 inch before the accelerated wear test. The thickness of the seal coats decreased due to the wear test as their aggregate particles were rearranged into a "flat" position. The after AWD thickness, as shown in Table XIII, ranged from 0.11 inch to 0.31 inch.

Accelerated Wear and Stripping Test

The trapezoidal sample plates containing the seal coat specimen were subjected to the effects of a rubber tire traveling over the surface of the seal coat on the accelerated wear device. The sample plates themselves were designed to fit tightly against each other around the circular path of the tires. This provided the wheel assembly a continuous surface to travel over. The asphalt sample plates were placed on 0.12 inch thick aluminum plates, cut to the same size as the asphalt sample plates and the entire specimen clamped using the wooden retaining curbs to the AWD. The photograph of Figure 37 shows the specimens installed on the AWD ready for testing. Since the area under the center of the sample plate is hollow (originally cut to hold 4 inch diameter Marshall

Figure 37. Seal Coat Specimens Attached to AWD Track, Ready for Testing

specimens), the aluminum sample plates gave adequate support to the seal coat specimen but did allow for some surface deflection as the wheels passed over the specimen.

As previously stated, the number of wheel passes and test temperature for each cycle are shown in Table VII. At the end of each temperature-wheel pass cycle the seal coat specimens were removed and weighed to determine their weight loss. Figure 38 is a photograph of the specimens on the AWD after completion of 30,000 wheel passes. The end point of termination of the AWD test was at 30,000 wheel passes because some of the seal coats had lost about 50 percent of their weight and created a rather noticable bump as the wheels passed from one specimen to the next.

A graph relating the percentage of specimen weight loss with number of wheel passes was prepared for each seal coat job. Figure 39 presents a typical plot for the crushed stone seal coats. The graph indicates a loss of 23 percent weight for Route 58-0, 31 percent for Route 95-2 and 36 percent for Route 7-13 at the end of 30,000 wheel passes. A greater proportional amount of aggregate and asphalt was removed from the specimens during the hot and cold temperature cycles. This is seen on Figure 39 to have occurred where the slope of the weight loss curve is steepest, between 2,000 and 10,000 wheel passes and 20,000 to 24,000 wheel passes. The best fitted curves for crushed stone were of the linear weight loss versus logarithm of the number of wheel passes. Most of the data analysis gave an R value of 0.98 or better in relating weight loss to number of wheel passes.

The typical wear or weight loss curves from the AWD test for pea gravels is shown in Figure 40. The pea gravel seal coats, Routes and

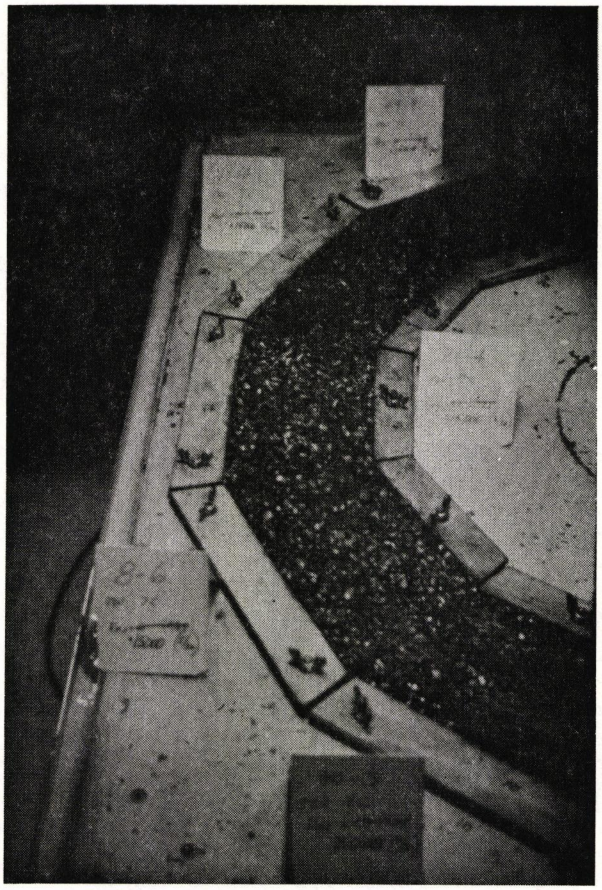


Figure 38. Seal Coat Specimens After Completion of 30,000 Wheel Passes

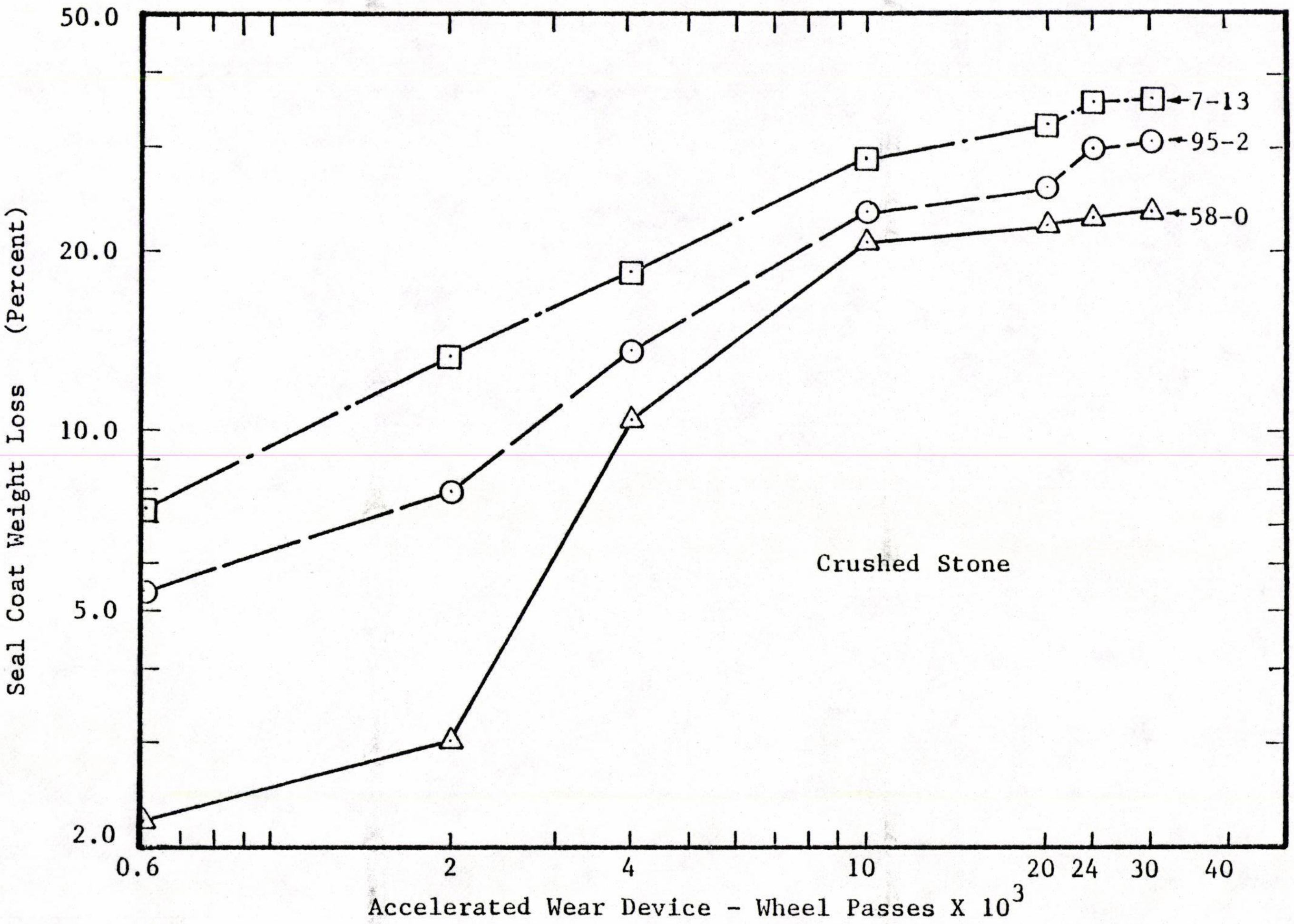


Figure 39. Relationship Between Specimen Weight Loss and Number of Wheel Passes for Crushed Stone on Routes 58-0, 95-2 and 7-13

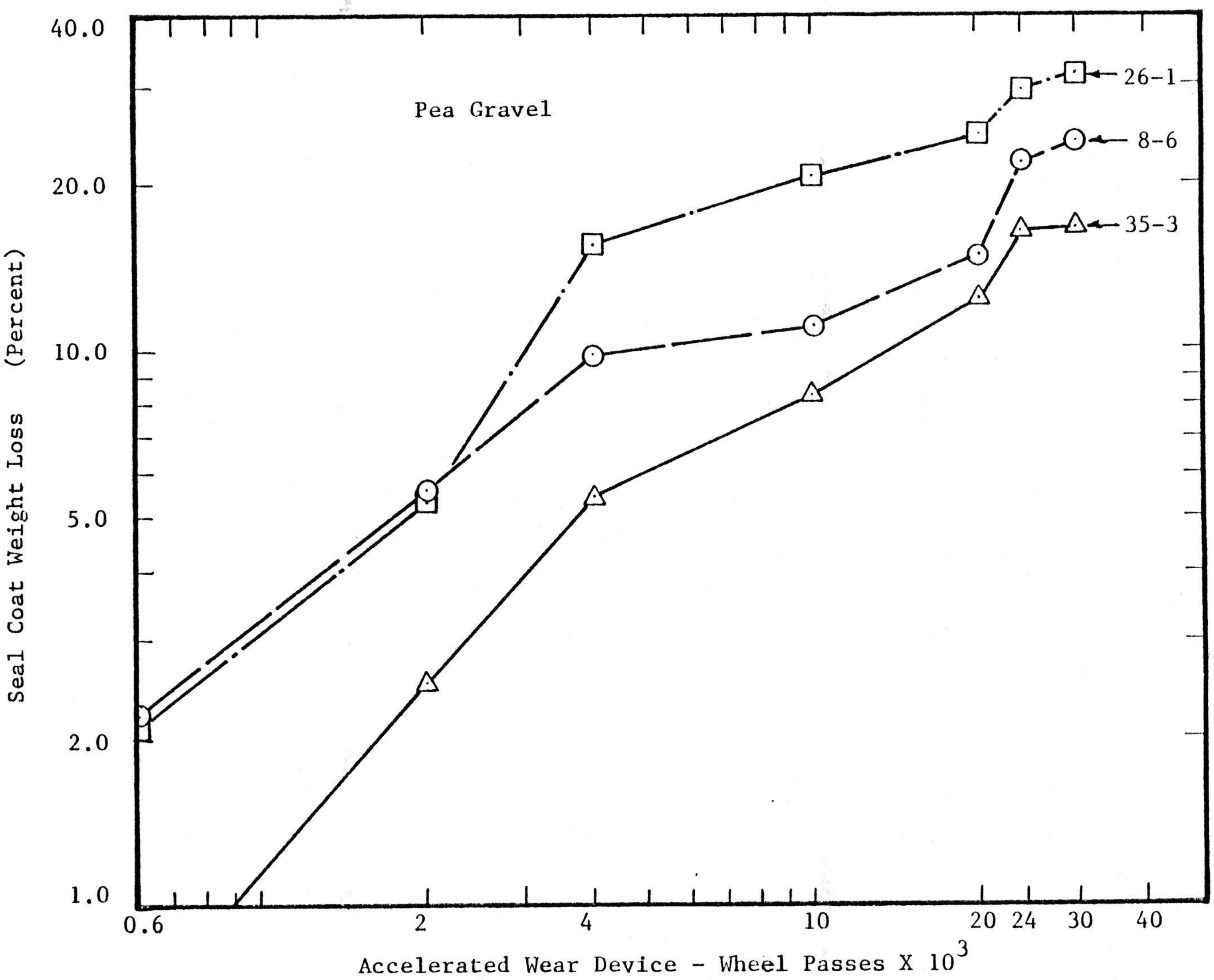


Figure 40. Relationship Between Specimen Weight Loss and Number of Wheel Passes for Pea Gravel, on Routes 35-3, 8-6 and 26-1

weight loss, respectively were: 35-3, 17 percent; 8-6, 24 percent; and 26-1, 32 percent. The pea gravel specimens also lost a more proportional amount of their material during the hot and cold cycles. The less durable seal coats tended to lose more material during the second heat cycle from 20,000 to 24,000 wheel passes.

Figure 41 shows the AWD test results that were typical of seal coats made with the Special Mineral Aggregate. At 30,000 wheel passes, Route 49-9 lost 35 percent of it's weight, Route 1-14 lost 43 percent and Route 75-5 lost 48 percent of its weight. As before, a larger proportional amount of the specimens weight was dislodged by the rubber tires during the hot and cold cycles of the AWD tests.

The circular motion of the wheels on the AWD tended to displace the seal coat materials by shoving the aggregates and the adhering asphalt in a tangential direction along the path of the wheels. The aggregate also tended to be pushed toward the inside of the wheel, the wooden curbs prevented the excess loss of material in this direction. Periodically, the surface of the seal coats was brushed transversely to keep the specimen surface clean of loose material so that it would not be picked up by the tires.

The results of the AWD test on each seal coat job are shown in Table XIV. All of the seal coats were subjected to 30,000 wheel passes. The most resistant seal coat was on Route 35-3, with an average weight loss of 17 percent; the least resistant seal coat was on Route 75-5, with 47 percent weight loss.

All of the seal coat, CRS-2 emulsion, base asphalt and aggregate test values were correlated with their respective AWD weight loss. The relationship between CRS-2 residual asphalt penetration and AWD weight

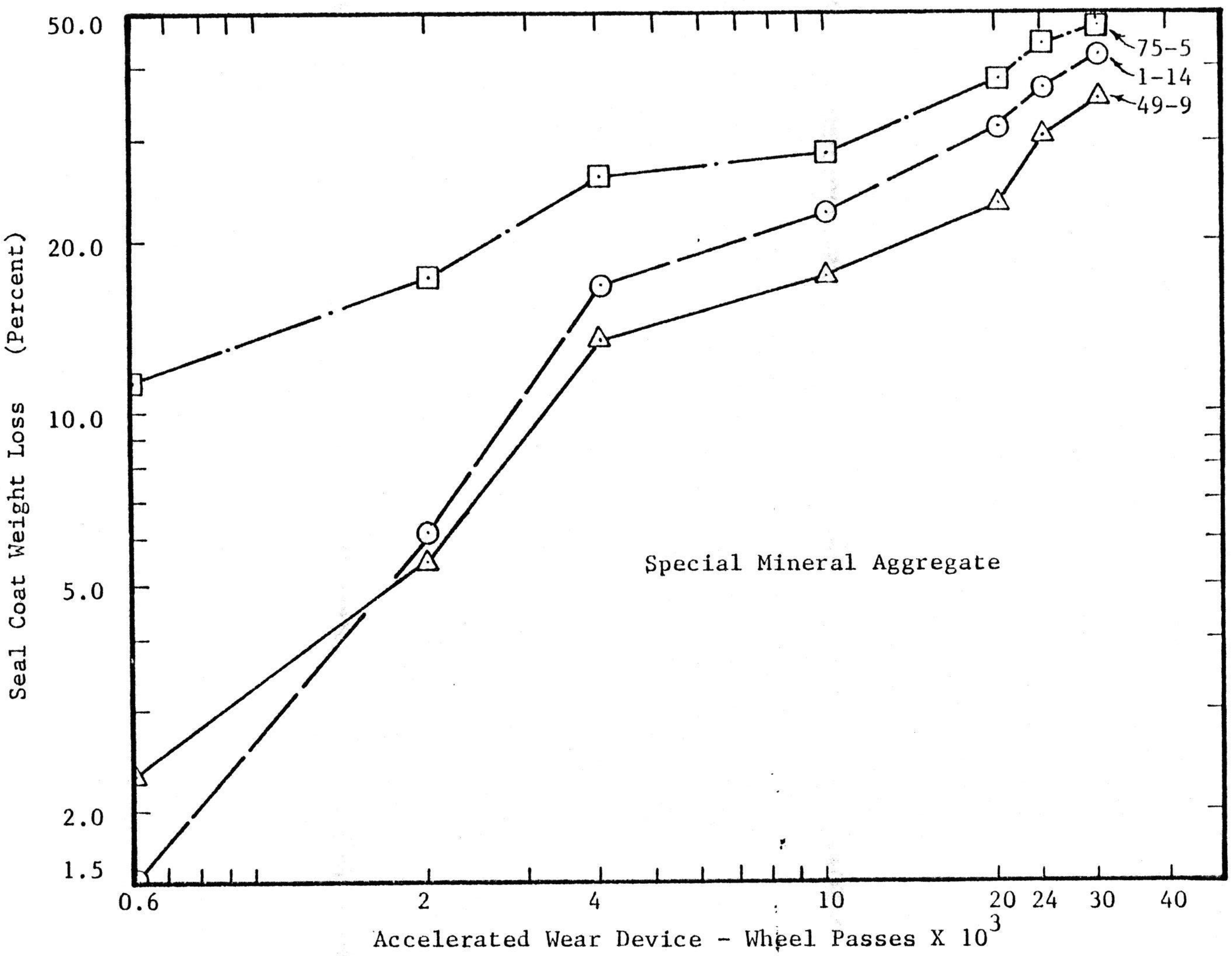


Figure 41. Relationship Between Specimen Weight Loss and Number of Wheel Passes for Special Mineral Aggregate on Routes 49-9, 1-14 and 75-5.

TABLE XIV

SEAL COAT WEAR TEST AND STRIPPING TEST RESULTS

No.	R-S	ACC. Wear Test		Panel Stripping	Film Stripping		
		30,000 Passes	80,000 Passes		Coating	Retention	Loss in Washing-%
		% Wt. Loss	% Wt. Loss	% Wt. Loss	% Coated	% Coated	
1	58-0	20.7	17.2	0.3	95	18	77
2	102-1	18.9	18.1	0.9	95	60	35
3	95-2	33.3	-	5.5	70	40	30
4	348-2	38.2	-	7.2	60	40	20
5	7-13	36.4	-	10.7	95	44	51
6	8-6	29.0	-	5.4	20	10	10
7	21-4	18.6	18.2	1.9	50	40	10
8	37-2	20.7	24.6	2.3	20	10	10
9	82-2	33.6	-	8.6	25	10	15
10	31-1	27.9	39.0	2.8	95	35	60
11	35-3	17.4	23.6	6.2	15	5	10
12	26-1	36.0	-	4.4	20	10	10
13	49-9	27.0	-	1.0	95	70	25
14	130-6	34.6	-	12.5	99	21	78
15	1-14	42.1	-	5.5	95	80	15
16	90-3	42.5	-	20.9	65	20	45
17	75-5	47.1	-	10.2	95	70	25

loss percentage is shown in Figure 42. The seal coat weight loss increased as the penetration of the residual CRS-2 increased. The various types of aggregate used in the seal coats are indicated on Figure 42; there is no trend obvious between wear and type of aggregate. The R value for the AWD wear versus penetration was 0.51. There is a definite trend indicated that once the aggregate is embedded in the harder asphalt, it is held more firmly against removal by the effects of traffic than with a softer asphalt.

The best correlation of AWD wear with the seal coat physical test values is shown in Figure 43, where the relationship between panel stripping and AWD weight loss has an R value of 0.70. The panel stripping values in Figure 43 are indicated by type of aggregate (crushed stone, pea gravel and crushed pea gravel); no trend was noted between panel stripping and type of aggregate.

The stripping test results are shown in Table XIV for both panel stripping (the seal coat specimen) and film stripping (CRS-2 with job aggregate). There were very low correlations between the film stripping test results and other test values. For example, an R value of 0.28 was obtained when film stripping was compared with panel stripping; film stripping with AWD weight loss had an R value of 0.27. The test values reported in Table XIV for film stripping are threefold: coating, retention and their difference due to washing the freshly coated aggregate under running water. The values in coating ranged from 99 percent down to 15 percent. The five emulsions having 25 percent or less coated material behaved as follows: the CRS-2 emulsion would coat or cover the aggregate well during the first 2 or 3 minutes of the 5 minute mixing period, then with continued mixing time the emulsion would begin to foam

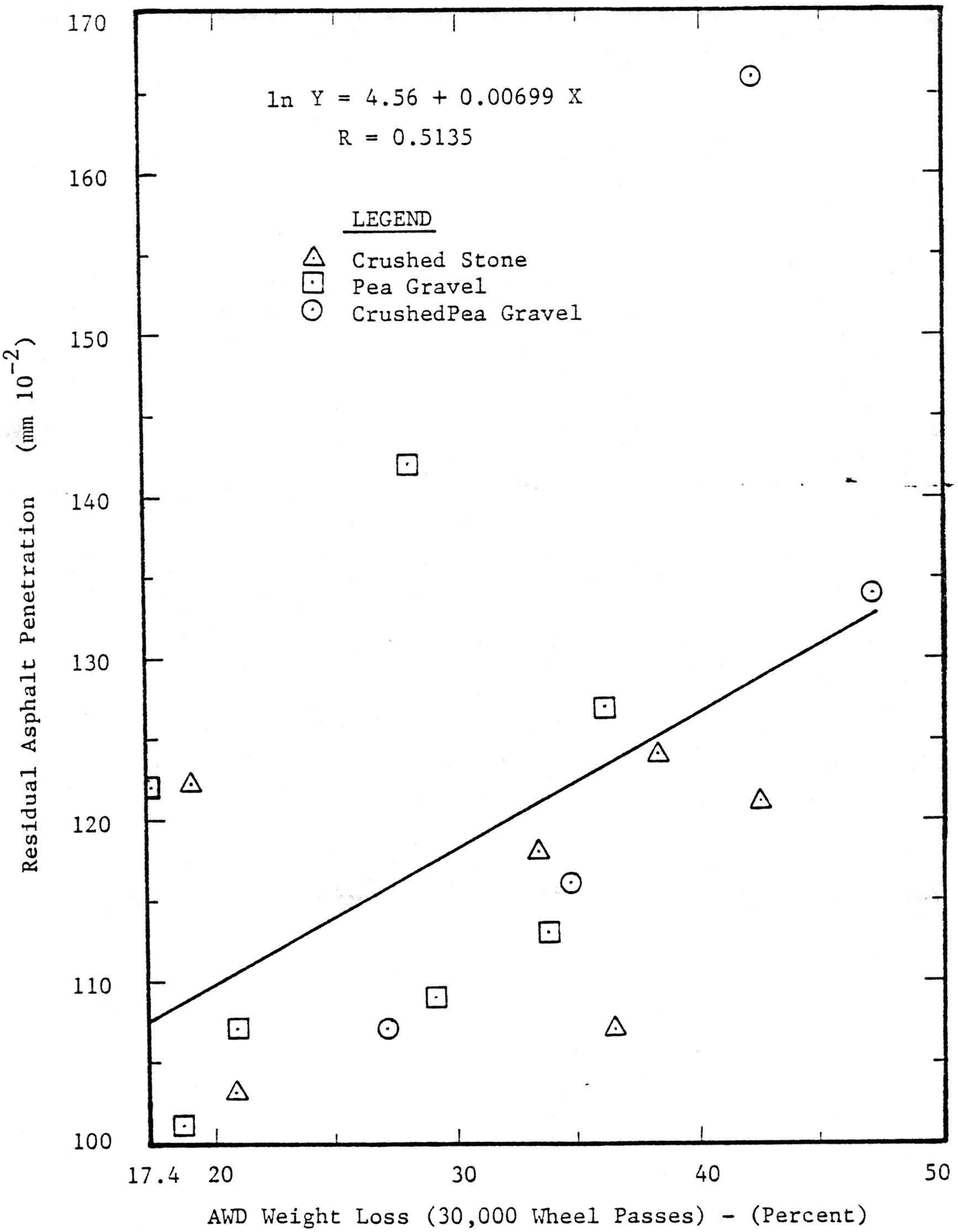


Figure 42. Relationship Between Residual Asphalt Penetration Versus AWD Weight Loss

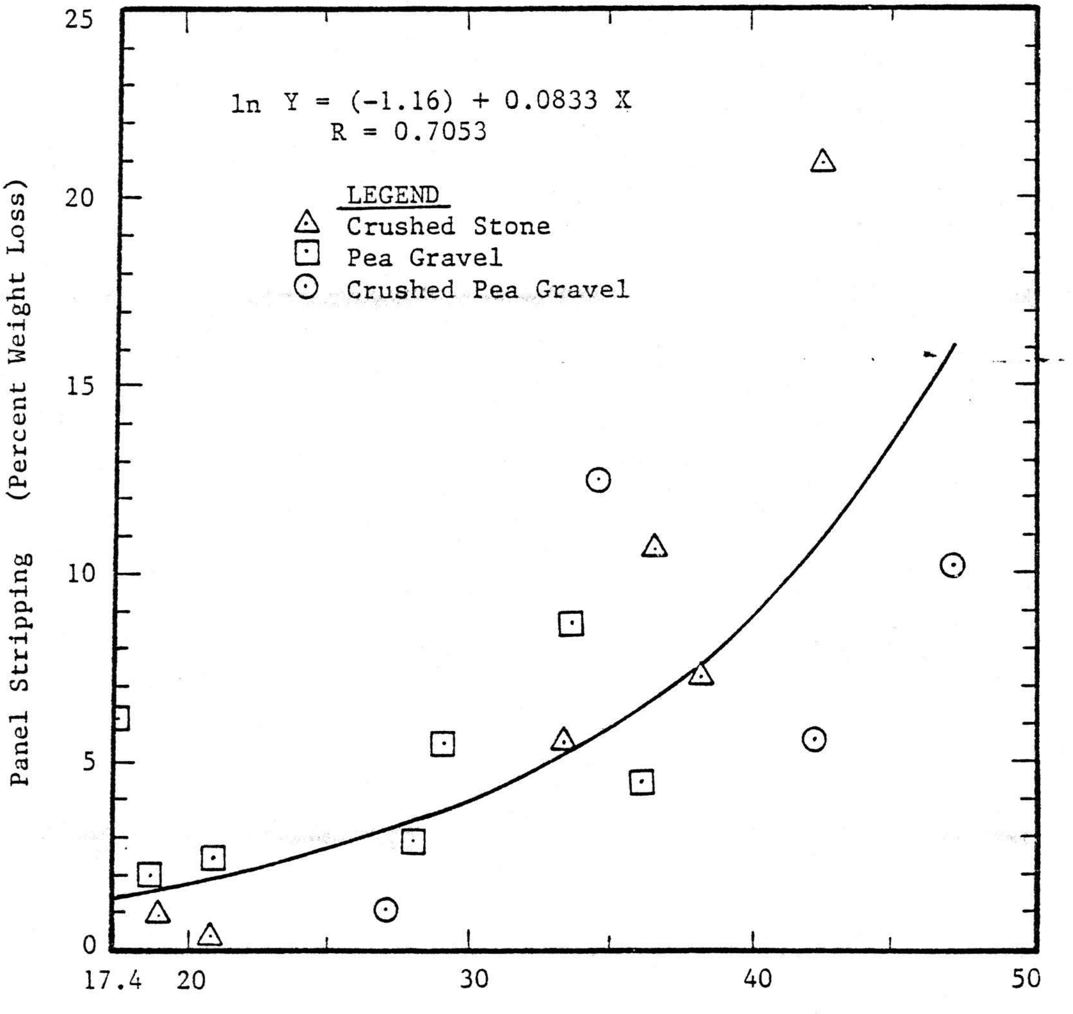


Figure 43. Relationship Between Panel Stripping and AWD Weight Loss

and uncoat the aggregate. No explanation for this behavior of the emulsion is known; the phenomenon could be related to the shelf life of the CRS-2 since the samples of CRS-2 had been stored in the laboratory about 6 to 8 months before the film stripping test was performed.

The film stripping retention values ranged from a low of 5 percent for Route 35-3 to a high 80 percent for Route 1-14. Of interest is that the Route 35-3 seal coat had an AWD weight loss of 17.4 percent contrasted with Route 1-14's AWD weight loss of 42.1 percent.

Relative Seal Coat Durability

All of the AWD test seal coat specimens were retained until the completion of the 30,000 wheel pass test cycles. The best six specimens of the seal coats were again tested on the AWD to a total of 80,000 wheel passes, being weighed at the end of 40,000, 50,000, 60,000, 70,000 and 80,000 wheel passes. The results of this extended AWD test are reported in Table XIV. The relative durability of these six seal coats by Routes and weight loss percent, respectively, are: Route 58-0, 17.2; Route 102-1, 18.1; Route 21-4, 18.2; Route 35-3, 23.6; Route 37-2, 24.6; and route 31-1, 39.0. The additional 50,000 wheel passes of the AWD caused more damage to Route 35-3 than to the Routes 58-0, 102-1 and 21-4.

A plot of seal coat weight loss, by job, for this extended wear test is shown in Figure 44. It can be seen that the wear of these "best" specimens remained at a constant rate until after 60,000 wheel passes, when Routes 35-3, 37-2 and 31-1 experienced more extensive weight loss than did Route 58-0, 102-1 and 21-4. It is noted that the wheels of the accelerated Wear Device passed over the seal coats for a total of 33.3

TABLE XV

RANK OF SEAL COATS, FIELD RATING AND ASPHALT FACTORS

Id. No.	Route-Section	Rank No.	AWD % Retention	Field Condition Rating-% (3-82)	Compaction Factor
11	35-3	1	82.6	98	15.5
7	21-4	2	81.4	95	19.7
2	102-1	3	81.1	97	23.5
1	58-0	4	79.3	88	39.3
8	37-2	5	79.3	87	36.5
13	49-9	6	73.0	89	19.5
10	31-1	7	72.1	91	14.8
6	8-6	8	71.0	81	17.4
3	95-2	9	66.7	93	21.1
9	82-2	10	66.4	74	16.7
14	130-6	11	65.4	75	21.8
12	26-1	12	64.0	93	15.8
5	7-13	13	63.6	85	9.6
4	348-2	14	61.8	95	8.8
15	1-14	15	57.9	90	4.3
16	90-3	16	57.5	91	9.9
17	75-5	17	52.9	79	9.6

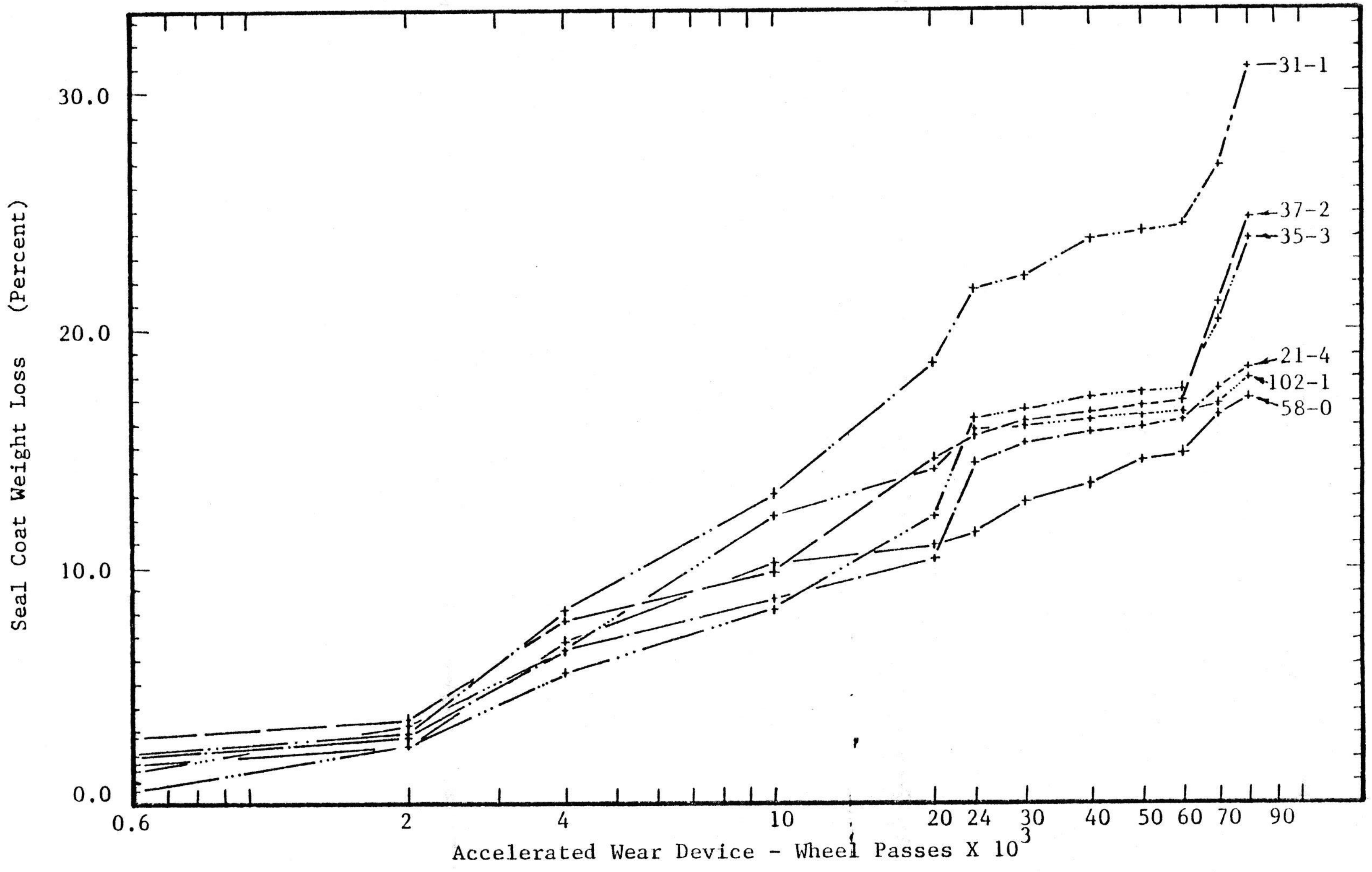


Figure 44. Relationship Between Seal Coat Weight Loss to 80,000 AWD Wheel Passes (Selected Specimen)

hours in the extended wear test, compared with only a total of 12.5 hours in the regular test procedure.

The 17 seal coat jobs of this study are ranked by descending order of resistance to wear in Table XV. This ranking is based upon the results of the 30,000 wheel pass test with the AWD. Also shown in Table XV are the results of the field condition rating survey performed in March 1982 by AHTD personnel and a compaction factor for each job.

The AWD retention values were correlated with the field condition ratings. A low coefficient of correlation of 0.42 was obtained for the best fitted curve with this data.

A better relationship between the asphalt properties and AWD weight retained was obtained by considering the roller compaction effects along with the viscosity/softening point ratio. This relationship is shown in Figure 45 where the best fitted curve shown has an R value of 0.74. A higher roller compaction effect gave a better retention of the seal coat materials during the AWD test. This roller compaction factor was obtained by dividing the absolute viscosity by its softening point and multiplying by the number of rollers used on the seal coat project. A better correlation with AWD wear would be expected by using the actual number of roller passes over the seal coat sample along with the relative tire (or wheel) contact pressure of the rollers. The roller compaction effect may indicate the relative ease of embedment of the aggregate into the CRS-2 emulsion during construction.

A more severe test condition using the AWD was initially planned. This condition was to add a wet-dry cycle at cold and hot temperatures and to determine the amount of aggregate detachment due to moisture effects. This was not done in this research because of the time

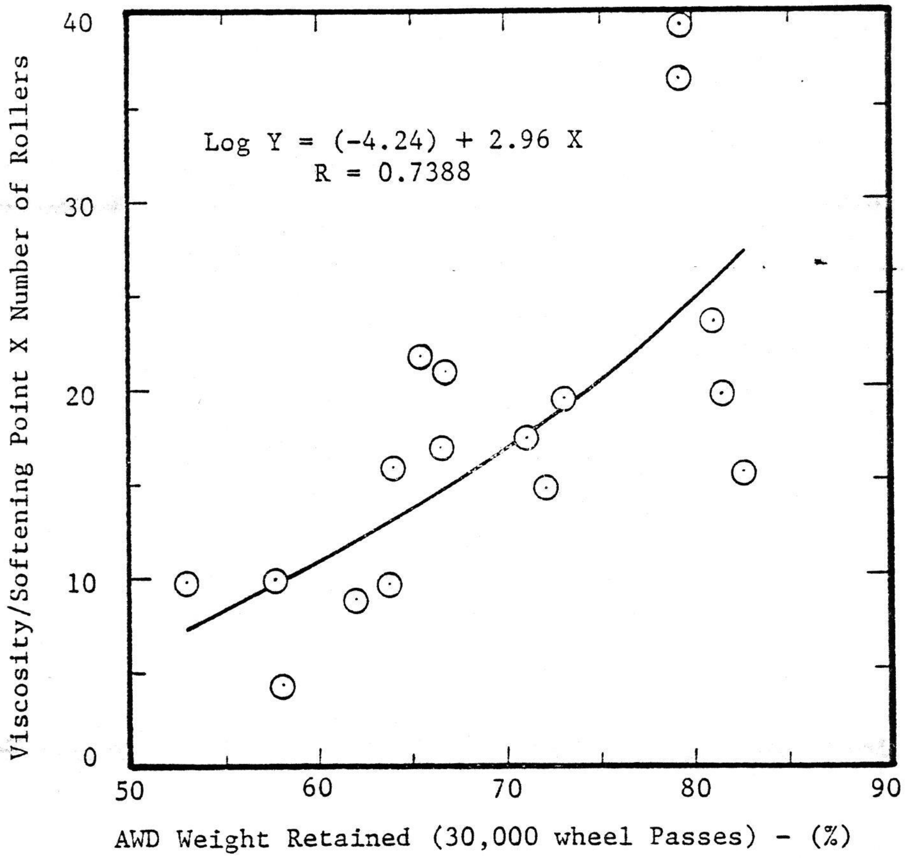


Figure 45. Relationship Between Viscosity/Softening Point Times the Number of Rollers Versus AWD Weight Loss

required to air dry the samples in between test cycles. This wet-dry cycle would be feasible if all 12 of the test specimen on the AWD were of the same seal coat material, then the loose material on the test track surface may be recovered, dried and weighed to determine the amount of weight loss.

It is noted that the only factor that varied between different runs on the AWD test was the temperature of the samples on the track. The hot temperature cycle had to be controlled very closely in order to obtain repeatibility between duplicate sets of seal coat samples. A variation of about 5 percent weight loss between duplicate test samples was experienced. The average value of these duplicate test results have been used in determining the relative durability of the seal coats investigated.

Summary

The physical characteristics of the seal coats investigated and their parent materials have been presented in tabular and graphical form. Some of the more significant relationships between the seal coat variables have been discussed. The gradation of the aggregates extracted from the seal coats varied from their specified gradation in 12 out of the 17 samples. The CRS-2 asphalt emulsion was within the specification limits of ASTM D 2397 (33) for all samples except for the Saybolt viscosity on Route 75-5.

For further discussion purposes some of these test results have been placed on the bar graph of Figure 46 along with the AWD percentage surface retained for each seal coat under study. The results of the AWD test indicate that some of the seal coats are more resistant to wear

AC gal/yd^2	Agg lb/yd^2	Panel strip, %	P50 in.	Route-Section	Ag/AC PPG
0.23	22	0.3	0.28	58-0	96
0.30	21	0.9	0.24	102-1	70
0.21	17	1.9	0.22	21-4	81
0.23	17	6.2	0.23	35-3	74
0.17	16	2.3	0.24	37-2	94
0.16	8.7	1.0	0.16	49-9	54
0.19	15	2.8	0.18	31-1	79
0.18	18	5.4	0.16	8-6	100
0.20	17	5.5	0.29	95-2	85
0.22	20	8.6	0.22	82-2	91
0.12	9.0	12.5	0.22	130-6	75
0.18	21	4.4	0.24	26-1	117
0.21	13	10.7	0.23	7-13	62
0.26	18	7.2	0.30	348-2	69
0.13	11	5.5	0.17	1-14	85
0.12	9.7	20.9	0.14	90-3	81
0.14	10	10.2	0.19	75-5	71

TEST RESULTS

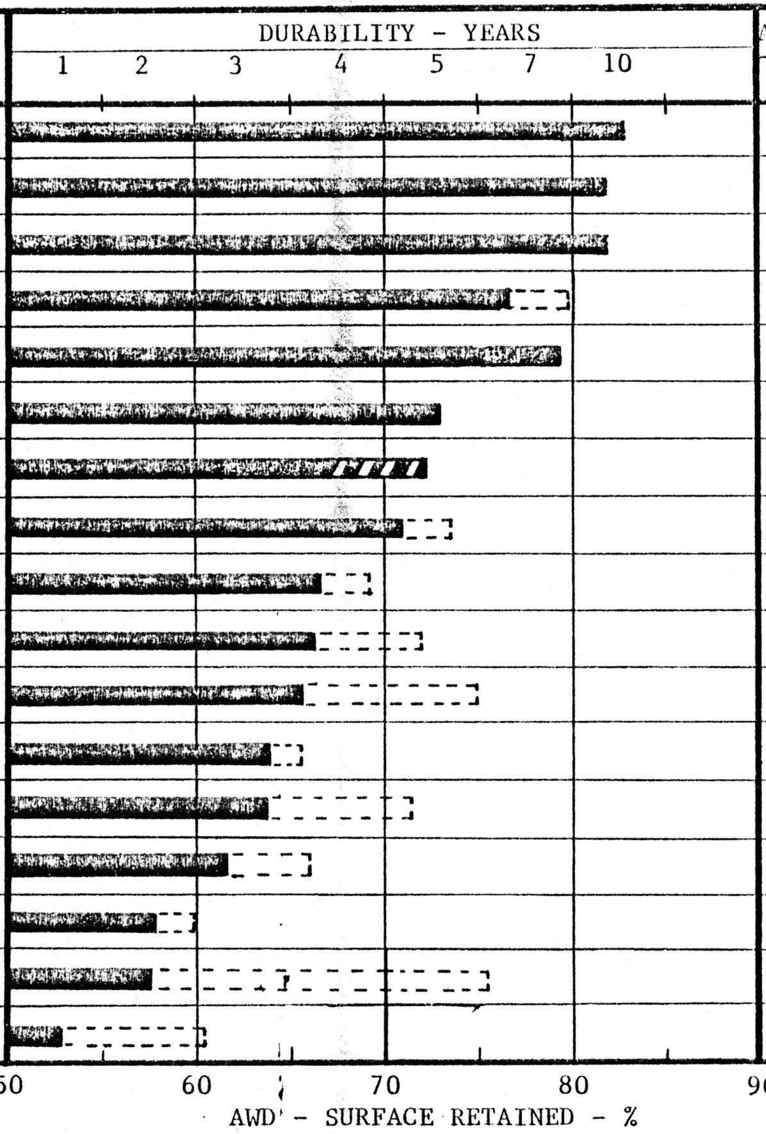


Figure 46. AWD Durability and Test Results

than others, having a range of wear from 55 to 80 percent under conditions of the test. The differences between the various aggregates, emulsions, construction equipment and techniques used in constructing these seals contributed to this differential wear.

The initial embedment of the aggregate into the CRS-2 during construction seems to be a major factor in the seal coats wear resistance. It is proposed that the relative initial aggregate embedment is indicated by the panel stripping percentages, which are shown in Figure 46. The panel stripping test may reflect some stripping tendencies of the aggregate and asphalt, but the one hour static soaking time in 130 F water was too brief to cause debonding of very much asphalt from the aggregate. Any weight loss over 3 percent could be attributed to lack of embedment of the aggregate into the asphalt. On this basis then, the adjusted AWD wear values would be changed considerably to that indicated by the dotted lines on the ends of the AWD bar graph of Figure 46. The factor that might counteract this increase in the AWD retention is the lack of sufficient asphalt to hold these aggregates in place.

Based on the results of this investigation, discussion and field observations a relative durability of the seal coat projects included in this study are shown in Figure 46. Their seal coat service life is estimated to range from 2 to 10 years. The seal coats of Routes 58-0, 102-1, 21-4, 35-3 and 37-2 have a predicted service life of 7 to 10 years. A service life for the seal coats of Routes 49-9, 31-1 and 8-6 is estimated to be from 5 to 7 years. The other seal coat projects have an estimated service life of 4 years or less. The actual service life of these seal coats will vary with traffic and environmental factors.

Seal Coat Design

The proper amount of asphalt and aggregate to use on a seal coat project must be tempered with judgment by the design engineer regarding the conditions in the field. These conditions include: traffic over the road, physical characteristics and condition of the seal coat aggregate, asphalt properties, absorption of the underlying surface and waste. The use of good materials and construction procedures, with attention to details of workmanship, will permit the seal coat designed to provide the best possible service.

Evaluation of the physical composition of the six most durable seal coats under investigation indicate desirable relationships that may be used for future seal coat designs. The factors that are common to the better seal coats include: P50 particle size, quantity of aggregate, the aggregate-asphalt ratio and high AWD durability. The aggregate-asphalt ratios shown in Figure 46 were obtained by dividing the aggregate weight by the asphalt weight, yielding pounds of aggregate per gallon of asphalt (PPG).

By regression analysis, the best fitted equations that related these factors were determined. These equations are:

(1) $\text{Ln P50} = -0.681 - 0.0394 \text{ AWD Loss}$ (with $R = 0.72$)

(2) $\text{Ln AGG/AC} = 3.28 + 4.66 \text{ P50}$ (with $R = 0.87$)

(3) $\text{Log AGG. WT.} = 2.32 + 1.71 \text{ Log P50}$ (with $R = 0.95$)

where: Ln = natural logarithm

Log = common logarithm

P50 = average particle size, inch

AWD Loss = % wear at 30,000 wheel passes

AGG/AC = Ratio Aggregate (PSY) to Asphalt (GSY), PPG

AGG. WT. = Aggregate weight (PSY)

The material quantities given by these equations are for a condition of fairly heavy traffic and no absorption of asphalt by the old pavement. The aggregate and asphalt characteristics should be similar to the materials investigated in this study.

An example of the use of these equations to select the proper quantity of aggregate and asphalt for a seal coat will illustrate the procedure. Select an approved aggregate source, with an average grain size of 0.25 inch. Using equation (2) the desired aggregate-asphalt ratio is determined.

$\text{Ln AGG/AC} = 3.28 + 4.66\ \text{P50}$, and

$\text{AGG/AC} = 85.2\ \text{PPG}$

then determine the amount of aggregate required, use equation (3),

$\text{Log AGG. WT.} = 2.32 + 1.71\ \text{Log P50}$, and

$\text{Aggregate} = 19.5\ \text{PSY}$

then the required amount of asphalt would be:

$\text{AC} = \text{AGG. WT/(AGG/AC)} = 19.5/85.2$ and

$\text{AC} = 0.229\ \text{GPY}$

The aggregate should be adjusted for waste, probably between 5 to 15 percent increase depending upon traffic and handling factors. The amount of asphalt will need to be increased up to 0.09 gal. per sq. yard if the old surface is porous, rough and oxidized. The amount of asphalt will need to be decreased by up to 0.03 gal. per sq. yard if the old surface is bleeding or flushed. Standard asphalt adjustment factors are as shown in the Basic Asphalt Emulsion Manual (8).

For lower traffic roads, the amount of asphalt should be increased to fill the greater voids that occur. The traffic classification and the adjustment factor for this procedure are, respectively: under 100 vpd, 1.31; 100 to 500 vpd, 1.15; 500 to 1000 vpd, 1.08; 1000 to 2000 vpd, 1.0; and over 2000 vpd, 0.92. In this example, if the design traffic is 100 to 500 vpd, the asphalt application rate (A) is:

$$A = 0.229\ (1.15) = 0.263\ \text{GPY}$$

Thus, to complete the example, assume a waste of 5 percent aggregate and the old pavement absorption is 0.04 gal. per sq. yard. Then the aggregate application rate (S) is:

$$S = 19.52\ (1.05) = 20.5\ \text{PSY},$$

and the asphalt application rate is:

$$A = 0.263 + 0.04 = 0.30\ \text{GPY},$$

then, if the CRS-2 has a residual asphalt content of 69 percent, the "shot rate" would be:

$$\text{shot rate} = 0.30/0.69 = 0.43\ \text{GPY}.$$

this shot rate is for 60 F, and must be increased for the higher application temperatures used in constructing seal coats.

The resistance to wear of the seal coat may be estimated using equation (1):

$$\text{Ln P50} = -\ 0.681 - 0.0394\ \text{AWD Loss, or}$$

$$\text{AWD Loss} = (L_m\ \text{P50} + 0.681)/(-\ 0.394)\text{, and}$$

$$\text{AWD Loss} = 17.9\%$$

This would indicate an 82.1 percent retention of the seal coat. Based upon Figure 46, the seal coat constructed with an asphalt of 0.23 GPY and covered with aggregate at the rate of 19.5 PSY would have a durability of 7 years or more.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the experimental work covered by this report and within the limitations of the test procedures and for the range of materials and conditions utilized in this investigation, the following conclusions are warranted:

1. The techniques developed and the equipment employed in this research work may be used to evaluate seal coat mix designs in the laboratory prior to their actual construction in the field. The procedures developed in this work may be used to evaluate actual field samples of seal coats as to their performance capability under varying environmental conditions. New types of binders and aggregates may be evaluated to determine their capability for use as a seal coat material.

2. The seal coat pavements constructed using class 7 or class 8 crushed stone and pea gravel aggregate provided a more durable pavement surface than did the seal coat pavements constructed using the crushed gravel material sized to meet the grading limits of a Special Mineral Aggregate.

3. Better embedment of aggregate was obtained on the seal coat samples where steel wheel rollers were used in conjunction with pneumatic tire rollers. There was some degradation of these seal coat aggregates which must be anticipated when steel wheel rollers are employed.

4. The seal coat pavements constructed with a harder residual asphalt (lower penetration and higher absolute viscosity) have a higher retention of their surface material in the Accelerated Wear Device test than do seal coats constructed with a softer residual asphalt.

5. The CRS-2 emulsion sampled and tested in this work meets the Arkansas State Highway and Transportation Department specifications in all tests, except for the Saybolt viscosity test on Route 75-5. The high Saybolt viscosity (950 seconds at 122 F) of the CRS-2 emulsion used may have been a contributing factor to the poor durability of the seal coat on Route 75-5 as indicated by the accelerated Wear Device test results.

6. There was no significant relationship established between the CRS-2 Saybolt viscosity test results and other measured properties of the CRS-2, base asphalt cement and the seal coat physical properties.

7. The CRS-2 sampling device shown in Figures 28 and 29 of the report provides an excellent means of taking samples of the emulsion.

8. There was very little change in the penetration, softening point, ductility and absolute viscosity of the asphalt cement that was used in the manufacture of the CRS-2 asphalt emulsion. The changes include: 12 of the 13 asphalt cement samples had a decrease in penetration, and 7 of the 13 asphalt cements had a decrease in their softening point after emulsification and recovery by distillation.

9. There is a very good correlation between the absolute viscosity of the parent base asphalt cement and the CRS-2 residual asphalt.

10. The measured abrasion pH of the aggregate and the flakiness index of the aggregate indicate no significant relationship with other test results obtained in this work.

11. The seal coat design procedure developed on the basis of the project test results may be used to design longer lasting and therefore more economical seal coats. The design method presented should be limited to materials similar to those evaluated in this study.

On the basis of the results of this investigation, the following recommendations are presented:

1. The specifications for aggregate grading limits should be revised as follows. Add the 3/8 inch sieve to the class 7 grading, with a limit of 18 to 45 percent retained. Add the No. 4 sieve to the class 8 grading, with a limit of 60 to 80 percent retained. This change would provide a more consistent aggregate material that would assist the sealing crews in their work.

2. A continued effort should be made to monitor the 17 seal coat projects investigated in this research work until they are resurfaced. A condition rating on a semi-annual basis (March and September) in the vicinity of where the field samples were obtained is suggested. The correlation of actual seal coat performance with their predicted service life as shown in Figure 46 of this report would provide insight into the relative merits of each seal coat investigated. Differential traffic and environmental effects should be considered in the analysis.

3. Notwithstanding the general opinion that Special Mineral Aggregate seals coats "do not break windshields", an evaluation of their true economy in view of their poor durability, as indicated by the results of this study, is warranted. The class 7 or class 8 aggregates used in the seal coat samples taken in this work indicated double the resistance to wear of a Special Mineral Aggregate seal coat.

4. Consideration should be given to insuring the initial embedment of the aggregate into the liquid emulsion during construction. This was accomplished by coordinating the speed of the distributor truck, chip spreader and rollers. The aggregate was placed and rolled as soon as possible after the application of the emulsion. The use of steel wheel

rollers and pneumatic wheel rollers with as high a contact pressure as the aggregate can withstand would contribute much to obtaining a good seal coat.

5. A copy of this published report should be sent to each district engineer, maintenance superintendent and sealing crew foreman. This investigation would not have been accomplished without their assistance.

6. Additional study or investigation of the other variables as they affect seal coat performance seems to be dictated by the results of this work. The following questions are raised. Was the poor performance indicated by the crushed gravel with the Special Mineral Aggregate caused by: the actual gradation, the mineral characteristics, texture, shape, or adhesion properties with CRS-2 emulsion? Perhaps a different construction technique with the crushed gravel would improve performance. Would a CRS-2 emulsion with 3 percent oil improve seal coat performance? What is the optimum emulsion spraying temperature to use? What roller contact pressure and number of passes to attain good embedment are required? Should extreme measures be taken to control (or prohibit) traffic over a fresh seal coat until it has cured sufficiently to hold the cover aggregate?

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APPENDIX A

Details of the Accelerated Wear Device

Figures A1 - A3

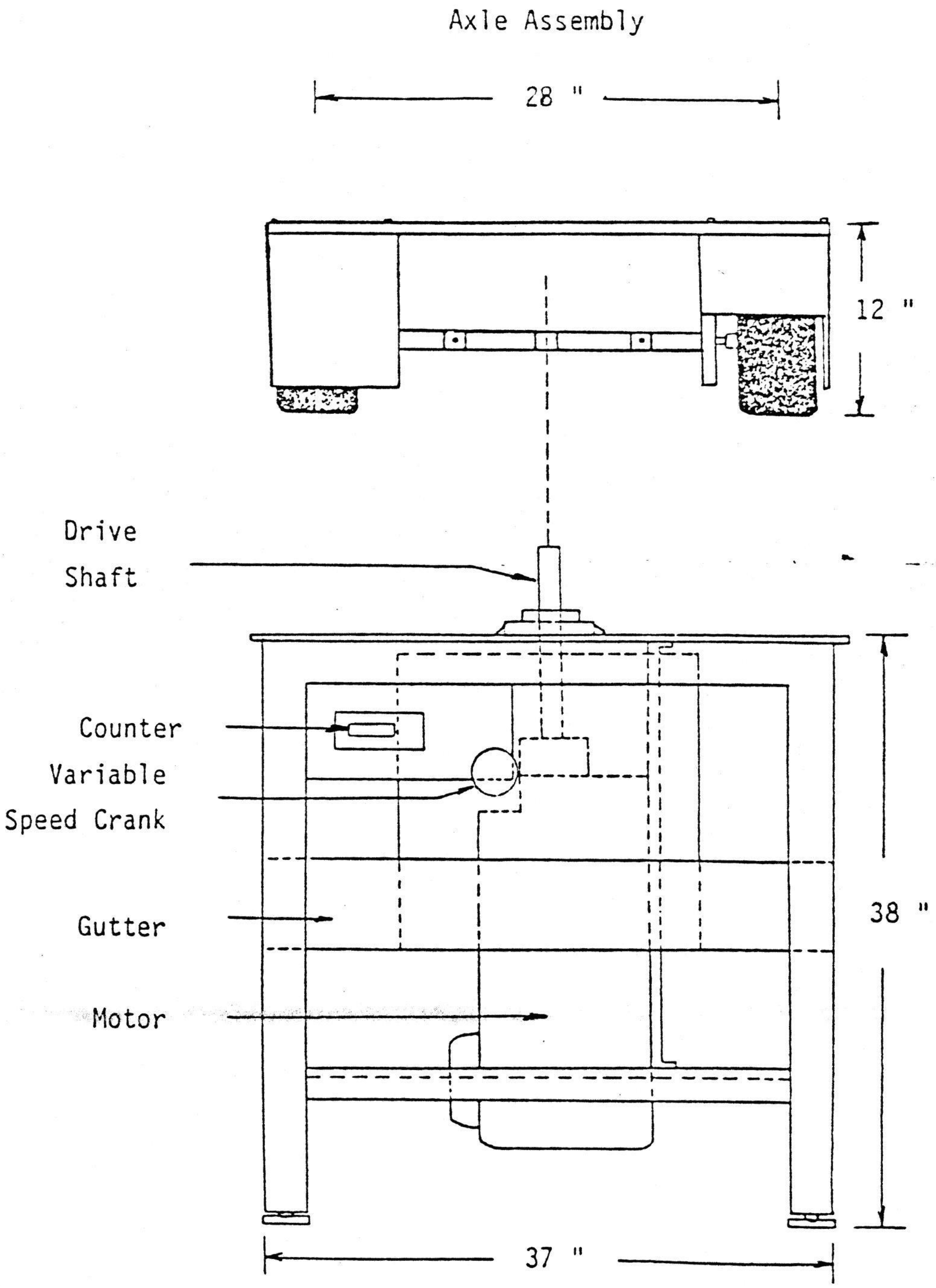

Figure A1. Accelerated Wear Device

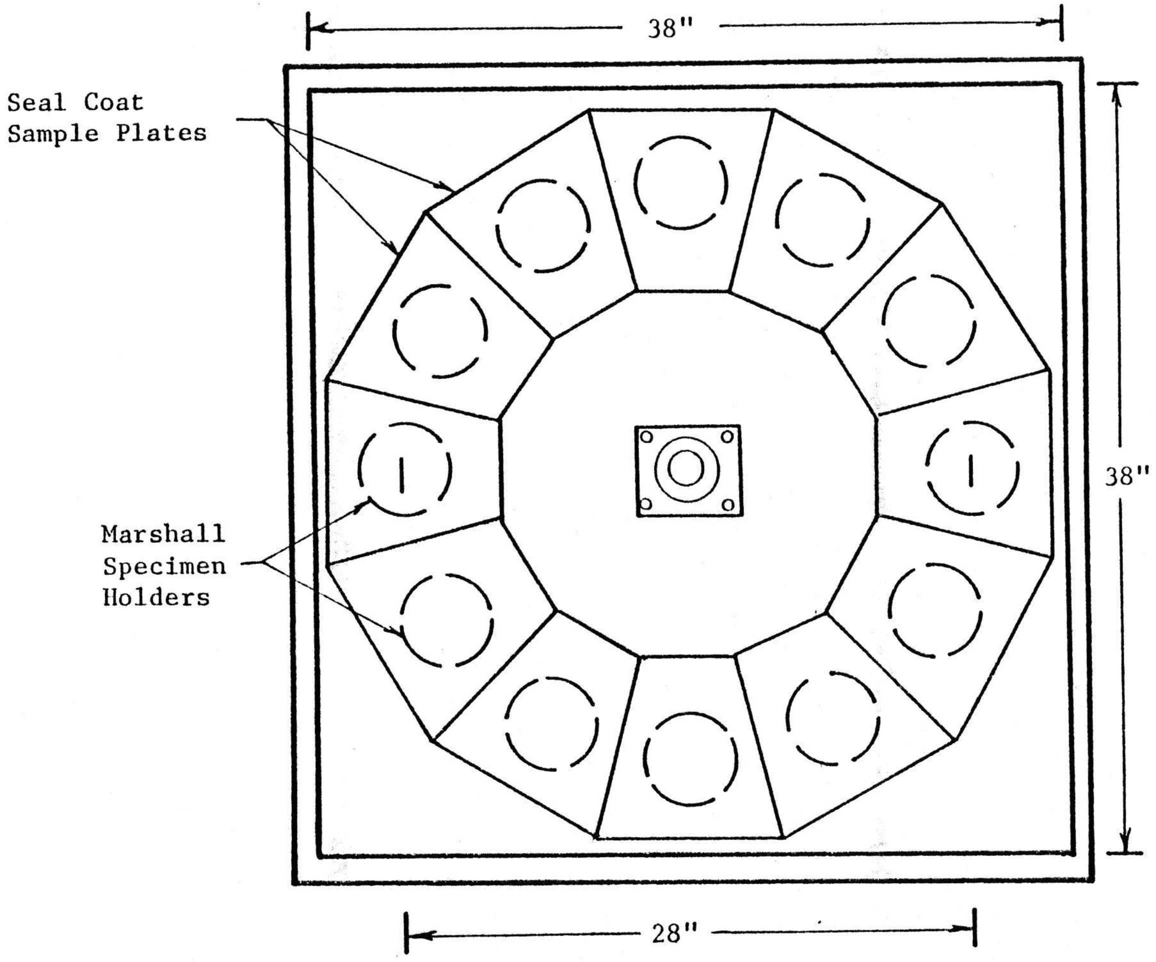

Figure A2. Accelerated Wear Device - Plan View

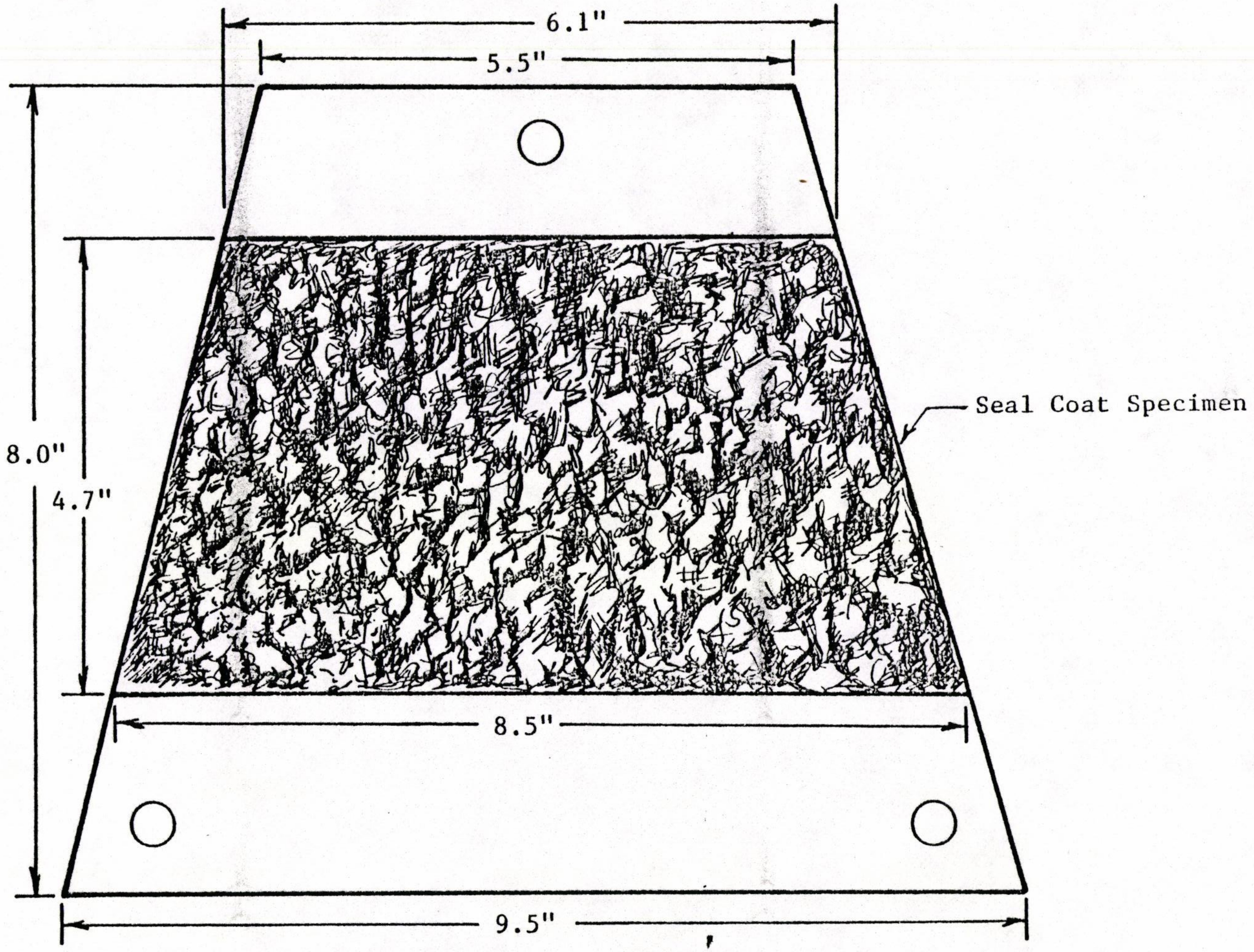

Figure A3. Accelerated Wear Device Seal Coat Specimen Plate