THE ADHESION OF BITUMINOUS MATERIALS TO MINERAL AGGREGATE

by

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Chapter I

GENERAL

Introduction

Asphalt as a construction material has been used since the days of pre-historic man. Some of the earliest records of history reveal that this substance was used even then as a cementing agent. Many of the most ancient castles, aqueducts, boats, and other structures used this material. It is believed that it was also used as the base for the dreaded "Greek Fire" which played such a large part in the naval battles of the early Hellenic days. However, it was not until the discovery of the great pits of Trinidad and the development of the Pennsylvania oil fields that asphalts and tars came into common usage as a cementing material in road construction.

In the refining process of the early petroleum fields, the main products desired were kerosene and lubricating oil. There was no demand for the modern gasoline and its present by-products. After the kerosene and lubricating oils had been distilled, the residue was pumped into large sump holes and allowed to seep back into the ground. Finally, it was used in the construction of city streets where it helped to meet the need as a protective surface for the rock-bound macadam. As all of the travel upon the streets in those days was by horse and horse-drawn vehicles, the lighter fractions of the residue had to be removed as a heavy asphalt was needed to prevent the horses' hoofs and the narrow steel tires of the wagons from cutting grooves in the pavement. From this beginning came the trend towards the use of the heavy paving grades of asphalt.

With the acceptance of the heavy grades of asphalt and tar, little change was made in the asphaltic concrete for many years. Of course, various mixes were designed for special conditions, but the main purpose was to provide a suitable wearing surface that would withstand the loads placed upon it and give a smooth riding surface. To achieve this, densely graded mixes with a high percentage of bitumen were used. If the mix had an excess of bitumen in it, and it tended to "bleed" (puddles of bitumen on the surface), little notice was made as the extra cementing material did not harm the surface. When the automobile became popular and the people demanded more surfaced highways on which to drive; this additional bitumen became dangerous as it made the pavement slick whenever it rained. To overcome this problem, the percentage of bitumen in the mix was reduced to approximately six percent; this amount of bitumen provided the necessary cementing material to hold the pavement together but was not enough to cause the obnoxious "bleeding". As the steel tires of the horse-drawn wagons had been replaced with the rubber tires of the automobile, the cutting and rutting of the surface of the pavement had been eliminated. In fact, the reduction in the amount of bitumen used increased the stability of the mix, giving better satisfaction.

Development of Modern Cutback Bitumens

The rapid increase in the number of automobiles brought about a greater demand for dustless all-weather roads, and the so-called "penetration" types of bituminous macadams were developed to meet this demand. While these types were called a new development in the field of bituminous construction, they were really a reversion to the original bituminous mixes which had proved unsatisfactory in the days of the horse-drawn vehicle. The change to pneumatic tires distributed the loads over a large enough area to prevent the destruction of the mat from this condition. These types of mats were cheap and easy to construct and many miles of them were laid. However, serious objections were developed that were not present in the old bituminous concrete. The penetration mats were much thinner causing them to break under the loads placed on the road. They were not as rigid as the older types and would deform readily, necessitating more maintenance to keep them in smooth riding condition. They were also subject to frost action which had not bothered the heavier types. However, the cost of the construction and maintenance of these mats was still much lower than the cost of the older types.

Most of the failures of the bituminous mats are due to mechanical means, but certain mats have failed from the inability of the bitumen to adhere to the aggregate. This phenomena usually occurs when water is present and where the water replaces the bitumen as the wetting agent surrounding the aggregate. Whenever this occurs, the bitumen that has been removed from the aggregate flows to the surface of the mat and lies there in puddles. The process which produces this phenomena is called "stripping" and the bitumen which flows to the surface is not excess asphalt or tar, but material that should be in use as a cementing agent in the mix. Of course, the mat is weakened whenever this occurs and the mat will usually fail at this point. Little or no aid from mechanical action is necessary to help produce this failure.

The conditions under which this stripping occurs may be very different from any other conditions which produce failures in the surface of the mat. If water is present in the subgrade of the road, the mat may fail from the pumping action of the loads passing over the mat. As water is practically incompressible, the bitumen is forced away from the aggregate, causing failure. If the roadbed settles, the mat may tend to crack and break into small fragments, especially if the mat is an old one in which the bitumen has been exposed to the action of the air which hardens the binding material and will not allow it to flow back together again. Or, the mat may fail from the heaving and thawing action of a heavy frost when the subgrade is saturated with water. These conditions are known to all engineers and are considered whenever a road is to be surfaced with a bituminous mixture. However, failure has occurred from none of these reasons and the only explanation that will satisfactorily explain why failure has occurred is the fact that certain bitumens in combination with certain aggregates will not bind themselves together in the way most bituminous mixtures do. There seems to be an inherent tendency of certain types of mineral aggregates to repel the wetting action of bituminous materials. While these aggregates may be coated with bitumen, if these coated particles are placed in the presence of water, the water will replace the bitumen, or, in other words "strip" the bitumen from the aggregate.

The introduction of the present cutback asphalts gave to the construction engineer a means by which the cementing material could be placed upon the surface of the aggregate with little or no heat, but they also increased the tendency of the aggregate to show its disinclination to adhere with the asphalts that had been applied to its surface. The lighter grades of asphalt do not have the asphaltene content of the heavy paving grades of asphalt and they, therefore, cannot suppress, to as great an extent, the entrance of water into the mixture. For this reason, most of the stripping failures have occurred in mats which have been laid with these cutback types of asphalts. The failure of the surface of the Salmon River Highway between Buell, Oregon, and Otis Junction, Oregon, in 1935 was due to this stripping action on aggregate that had been coated with RC-3 cutback asphalt. While the grade of asphalt cannot be blamed entirely for the failure of the mat, it shows the tendency of these lighter asphalts to allow this action to take place. All of the Western States have experienced the same difficulty with the use of the cutback asphalts that were never present in the older type of plant-mix bituminous concrete.

Correction of Failures

With the recognition of the cause of this type of failure in the bituminous mat, various investigators (2) (7) (8) (10) (12) have attempted to correct the underlying causes and to develop tests that will indicate the tendency of the mixture to resist failure from this cause. Excellent work has been done in this field by the various universities and state highway department laboratories throughout North America and Europe. As most of these investigations were carried out independently, the results obtained are not correlated with the work of other investigators. Consequently, the available information in this field must be used with the greatest care as there is no standard upon which the data may be compared.

Most of the work in this field has so far been in the development of a method whereby the adhesion of the bitumen and the mineral aggregate could be measured. Three general types of tests have been used; while two of these methods depend upon the agitation of the mixture of bitumen and aggregate in water, one of them rates the results by visual inspection, and the other method attempts to measure the amount of bitumen removed from the mix by separating the particles of aggregate from which the bitumen has been removed, and then determining the percentage of this recovered material as compared with the amount of aggregate originally coated. The third method measures the ability of the water to penetrate a bituminous mixture by recording the change in volume of the mix as the water enters. This type of test is known as a Swell Test. Many other types of tests have been advanced but they do not seem as applicable as the above mentioned do.

As one of the purposes of this investigation was to correlate the data obtainable by these various tests, one test of each of the three types was selected so the results could be compared with the data obtained by the use of the examples of the other types. While the results obtained may not be accepted as conclusive evidence for the action of each and every test devised to study this phenomena of stripping, it is felt that a general comparison can now be made between tests of these three types.

All three types of tests are the kind that must be run in a laboratory as they require special equipment to determine the data. In addition, the tests are also of the accelerated type which attempts to predict the behavior of the materials from tests over a short period of time. While the results of an accelerated test may not be the same as the results of a test that has been extended over a long period of time, if the results of the accelerated test can be used to accept or reject the material in question and are based upon standards that have been proved indicative of the action of the materials in question; there is no reason why a test of this type should not be used. It would be a very fine thing if it were possible to run extended tests over all materials used in construction work, but this is impossible to do. Usually when a material is subjected to a test, the results are wanted for immediate use and the shorter the length of time that is taken to obtain the required data, the better adapted the test is to the situation. As in the case of Portland Cement Concrete, it is obvious that better data could be obtained if the compression cylinders were allowed to cure for one or two years before they are tested. However it is possible to determine whether the concrete is acceptable or not from the results of the seven day fracture. It is the same in the field of bituminous materials. Before a test is to be considered acceptable for the determination of the stripping action, it must be able to give results in one week or less that will be comparable with the data resulting from the tests that extend over a longer period of time.

An accelerated test has a definite economic value. Usually when bitumen or an aggregate is sent to the laboratory to be tested, the contractor is waiting for the results of the test so he may continue work. As the bitumen is shipped to the contractor in railroad tank cars, there is a definite limit upon the length of time these cars may be used without the payment of demurrage. Likewise, the rock crushers can produce only a definite amount of aggregate in a day's time, and sufficient time must be given the crusher operator to produce the required amount of aggregate for the job. If the type of test used to determine whether the aggregate or the bitumen is acceptable for use upon the contract extends over a long period of time, the demurrage charges upon the tank cars containing the bitumen must be paid, and the crusher operator must be given an extension of time to produce the necessary aggregate. If the test used will give the required data in a short period of time, this type of test is more valuable even if the results obtained are not as accurate as produced by another test that takes a longer period of time to run. In modern construction work speed is as essential as accuracy. If it is possible to save a week's time or even one or two days by the use of a certain test, this is the type of test that should be used. Of course, the more accurate methods should not be discarded entirely as the results will prove valuable as a check upon the data received from the accelerated operation. By continued research and careful correlation of the results, it is possible to lessen the amount of time necessary to determine the necessary results.

Purposes of This Research

In the presentation of this thesis, it has been the author's intention to determine the resistance of stripping by various grades of bitumen now in use, the degree of hydrophobicity of aggregates available for construction in the State of Oregon, and the decision as to which of the three methods of testing the bituminous mixtures gave the most accurate results.

Chapter II

ADHESION THEORY OF BITUMINOUS MIXTURES

Types of Adhesion

In the discussion of the stripping of the bituminous film from the aggregate which it surrounds, some recognition should be given the role played by the adhesion of these two unlike materials. Adhesion itself is the resistance to separation of two adjoining materials; it may be of two types, specific and non-specific. The non-specific type of adhesion is due to the mechanical interlocking of the particles and may be caused by the solidification of the bituminous plugs within the pores of the aggregate (5). The introduction of the bitumen within these pores can be aided by the heating of the aggregate and the bitumen, by thinning the bitumen with a solvent, which is either volatilized or absorbed into the pores of the aggregate, or by the emulsification of the bitumen in water and the subsequent coagulation of the bitumen globules in the pore spaces of the aggregate.

Besides this non-specific or mechanical adhesion, there is the specific phenomena connected with the physical and chemical character of the mineral surface and of the bitumen. This phenomena may range from the purely physical type through oriented adsorption to the formation of insoluble compounds by the chemical action produced between the surfaces of the two materials. Previous investigations (12) have shown that the adhesion developed by the physical adsorption is almost negligible and may be disregarded. The primary interest in this type of adhesion should be placed upon the orientation phenomena that is present as this produces the largest amount of the adhesion developed between the materials.

Composition of Bitumens

Bitumens are composed of heterogeneous hydrocarbon compounds which are mainly aliphatic and aromatic in character (2). The asphalts are usually of the aliphatic type and are called saturated compounds as they cannot be changed readily. Tars contain a larger amount of the aromatic compounds and are subject to oxidation when exposed to air. While the aromatic compounds are in a sense detrimental to the service life of the bitumen as they oxidize easier than the aliphatic groups, they aid the bitumen in developing its primary adhesive qualities as they are more active when first used. In addition, the aromatic groups contain compounds which are known as asphaltenes. These compounds give the bitumen its adhesive values, and a petroleum crude that does not contain these compounds is valueless for use as a pavement cement.

Polar Adsorption

Physicists have shown that aromatic compounds are polar in nature (3) which explains why these compounds develop a greater amount of adhesion than substances which do not contain these compounds. Polar adsorption is one form of specific adhesion and it takes place with considerably more energy than purely physical adhesion. In explaining the part played by the polar adsorption, this action may be defined as the energy developed between the electro-magnetic fields surrounding any material. A polar material is one in which the molecules, or parts of the molecules, are surrounded by electro-magnetic fields due to the separation of the centers of gravity of the positive and negative charges of electricity in the molecule or in some part of it (12). Polar substances tend to be attracted to each other by the interaction and cancellation of parts of their electro-magnetic fields. A polar substance has very little attraction for a non-polar substance.

Dipolic Theory

One name that has been given to this attraction of unlike substances is the Dipolic Theory. This theory states that all forms of matter contain minute electrical charges, or dipoles. As two materials are brought together, these dipoles either attract or repel each other according to their orientation. If one of the materials is a liquid or a gas, those dipoles which repel each other will tend to shift upon their axes until the proper alignment is reached. It is this fact that accounts for the increase in adhesion of materials over a period of time. The more viscous a substance, the slower these dipoles will be in arranging themselves. For this reason, materials and liquids of low viscosity are more capable of adhering to a solid object. When a liquid is used in this manner, the attraction is called "wetting". Bartell (1) defines wetting as that phenomenon which occurs when a solid phase and a liquid phase come into contact in any manner, so as to form a solid-liquid interface. Through this process, it is possible for the bitumen to adhere to the aggregate.

Surface Energy Effects

When a surface has been wetted by another substance, a change takes place in the surface energy at the interface. A definite quantity of this energy is converted into free surface energy and is available for use. There are three types of wetting: adhesional, spreading, and immersional. The last is the type that takes place when a solid-air phase is changed to a solid-liquid phase. If the liquid possesses a high surface tension, a large amount of energy must be expended to complete the system. Liquids with a low surface tension, when placed upon a solid, will wet the solid more readily and with less expenditure of energy than will liquids of higher surface tension. While this is true, it is not correct to say that the liquids with the lower surface tensions will give the highest degree of wetting. As liquids with high surface tensions possess high free surface energy in adhesional and spreading wetting, these liquids will contribute part of their free energy to the wetting and will displace the liquids with lower surface tensions. While these two types of wetting act only during the mixing of a bitumen and an aggregate, they contribute to total free energy of the interface before immersion is completed.

In the wetting of an aggregate with a bitumen, there are two interfacial tensions to be considered. One between the solid and air, and the other between the solid and a liquid, water. As long as there is nothing to break the bituminous film, an unstable equilibrium is maintained. When the bituminous film is broken, it will heal itself if no outside medium is present. However, if water is present, the bitumen will flow to maintain a shape with the least surface area. Whenever this occurs, the bitumen will allow the water to penetrate to the aggregate. As the water enters the mixture, the bitumen will withdraw to give the smallest possible surface and the water will remove it from the aggregate.

When this occurs in the presence of water, a three-phase point is formed which is the point the bitumen, air, and water have in common. This point seems to occur first at the corners or edges of the aggregate where the bituminous film is stretched thin and the water is able to penetrate the oil. If agitation is used, the rolling action breaks the film at the edges by causing the particles to cut through the bituminous layer. At this three-phase point, the three interfacial tensions are in equilibrium or else flow will take place until equilibrium is reached (7).

This is the simple tri-component coplanar force system (Figure 1) simplified by the fact that forces b and c are opposed in the same straight line. If there is no film, force c is no longer free to move about on the surface of the aggregate and there is no stripping action.

This relation may be expressed as

$$c = b + a\cos\theta$$

is apparent or

θ is the angle whose cosine is $\frac{c-b}{a}$.

From this relation it may be shown that if c is greater than b, the bitumen will be stripped from the aggregate, while if b is greater then the bitumen will completely

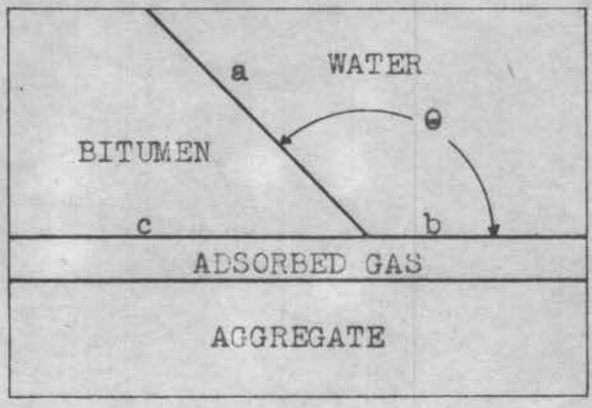

FIGURE 1

THREE-PHASE SYSTEM

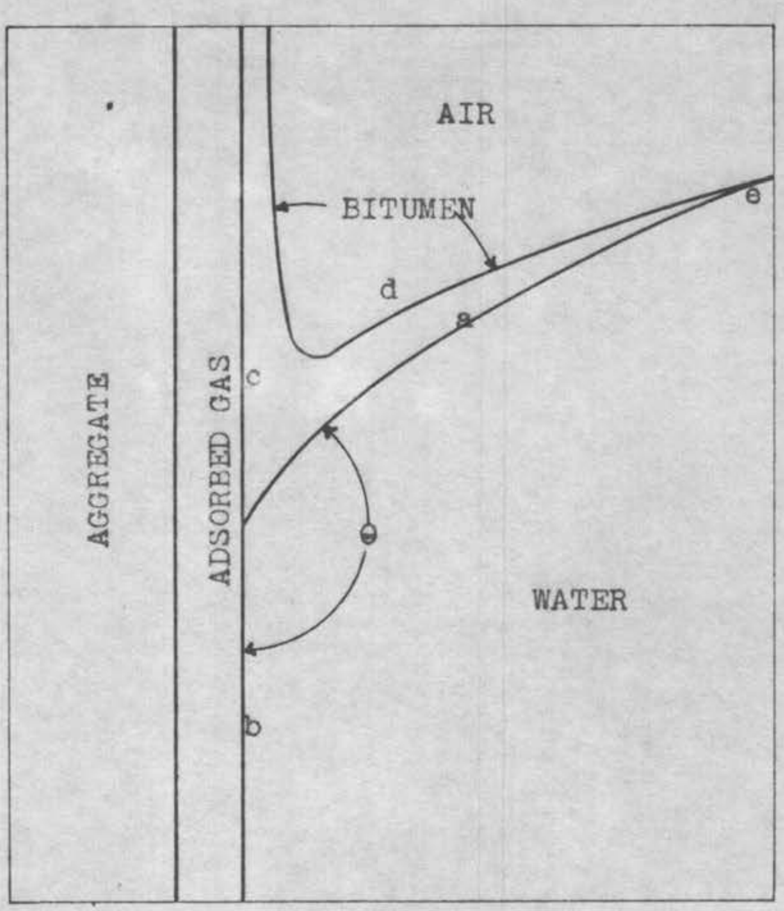

FIGURE 2

FOUR-PHASE SYSTEM

cover the aggregate in a perfectly stable film and still it would not be necessary for the bitumen to wet the mineral in any way.

In a pavement surface, this stripping is further complicated by the surface tension of the water. When the water is able to penetrate the bitumen surrounding the aggregate, the bitumen will have a tendency to go into the water-air interface, in this case the surface of the water bubble. This is caused by a different three-phase system in which equilibrium can never be reached if the surface of the water is great enough.

It can be seen (Figure 2) that if the sum of tensions a and d do not equal tension e, that e will pull the bitumen out indefinitely. Average values given by investigators (7) are d equals 25 to 39, a equals 15 to 21, and e equals 72, thus d plus a equals 40 to 60, while e is greater, being 72.

If this be so, then any bituminous film that surrounds a particle of aggregate without wetting it will always be stripped if water is allowed to penetrate the film.

Mr. R. J. Shaw of the Arizona State Highway Department (7), in recent investigations on the effect of air film surrounding a particle of aggregate when being mixed with a bitumen, has found that certain types of aggregate cling tenaciously to their coating of air while others allow it to be removed with ease. From his investigation, he has concluded that any aggregate that retains its layer of air will be susceptible to stripping after being coated with bitumen, while an aggregate that readily gives up its air film will show very little or no stripping. In summarizing his results, he concludes that an aggregate classed as hydrophobic aggregate is one which has a loosely bound film of air surrounding it, and a hydrophilic aggregate is one with a tightly held air film.

This explanation helps to clear up the difference existing between the hydrophobic and hydrophilic aggregates. If it is possible to cut the film of air surrounding the aggregate, the character of the aggregate would then be changed from hydrophilic to hydrophobic. This may be done by the use of cutting agents which will remove the air film allowing the bitumen to wet the aggregate and develop complete adhesion with it. If sufficient time is given the bitumen, it will cut the film of air and wet the surface of the aggregate as the bitumen possesses greater free surface energy than the air. However, this will take time and the introduction of water into the system will prevent the bitumen from spreading on the surface of the aggregate.

Many investigators (1) have attempted to measure the exact contact angles of the various air-liquid-solid systems but so far it has not been possible to determine the exact values. Undoubtedly, these attempts will in time prove to be of value, but at present the only accurate method of determining the reaction of water upon the bitumen-aggregate system is through the actual testing of the aggregate and bitumen in question.

Chapter III

TEST METHODS AND MATERIALS

Types of Tests

Many methods have been proposed to investigate this phenomena which is known as stripping. Of all of the methods that have been proposed, three of these are outstanding, both in their simplicity and the accuracy of their results. The Dow Test attempts to evaluate the adhesion between the aggregate and the bitumen by visual methods after the mixture of these two materials has been subjected to a shaking action in the presence of water. The mixture after the completion of the test is rated according to the amount of stripping that has taken place. If all of the aggregate remains coated with bitumen, it is rated as Excellent, if 0-25% stripping has taken place, it is rated as Fair, and if more than 25% of the aggregate shows stripping, it is rated as Poor. This method depends upon the accuracy of the observer for accurate determination of the results. No attempt is made to determine the exact percentage of the aggregate that has had the bitumen removed. It is entirely a qualitative method.

The Tremper Method is based upon the same principle of subjecting the mixture of aggregate and bitumen to the shaking action in the presence of water, but the material that has had the bitumen washed off of the aggregate is collected and weighed to give an accurate determination of the amount of stripping that has occurred.

The Wash Test is not based upon the shaking of the mixture with water, but upon the ability of the water to penetrate the mixture in a twenty-four hour period. As the water penetrates the mixture and wets the aggregate underneath the bituminous film, the mixture swells and the enlarged volume due to the presence of the water is recorded upon an Ames dial which records the swell in thousandths of an inch. If the recorded swell does not exceed certain arbitrary limits, the mixture is said to be satisfactory for construction purposes. The Wash Test is the easiest of the three methods used to determine the stripping action, but the comparison of the data obtained from this test with that received from the other methods seems to indicate that it should be used with caution.

Selection of Aggregates

As the stripping action is peculiar to mixtures of bitumen and rock, all of the aggregates used in this research were representative of the types of aggregate used in actual construction work. The Oregon State Highway Commission furnished the aggregate which was selected from stockpiles and quarries used in bituminous road construction. No particular attempt was made to select aggregate from any certain part of the state, but an effort was made to include as many of the different types of aggregate as possible. While the predominant aggregate used in this type of construction in the State of Oregon is basalt, many other types of aggregate are also used. Gabbro, shale, sandstone, and felsite are the main aggregates used wherever basalt is not available. All of these types as well as others were included so a comparison of the various types of mineral aggregate could be made.

Origin of Bitumens

All of the bitumen used was produced from the California crudes. Four grades of asphalts and one grade of tar were used. Every grade of bitumen used in the research is in actual use as a binding agent for bituminous mixtures. As the stripping phenomena seems to be confined to mats that have been laid by the penetration and road-mix macadams, the grades of bitumen employed were restricted to those grades applicable to these types of construction. Previous investigations upon this subject (4), using the heavier paving grades, indicate that these grades are not subject to the stripping action to any appreciable extent, so they were not used in this research. While some of the grades of bitumen used may be used in plant-mix types of construction, their main use has been in the penetration and road-mix types.

The grades of bitumen used conform with the American Association of Highway Officials standards for liquid road-binding materials. Five grades were used, RC-4, MC-2, SC-6, SC-2, and RT-8. Four of these are asphaltic types, and the RT-8 is a tar produced from the refining of petroleum residue. All are California crudes which are the most prevalent in the Pacific Coast area. These five materials are the main grades of bitumen used in this locality for construction work, and for this reason they were selected for this research.

The Dow Wash Test

The Dow Wash Test, which was used as an example of the qualitative methods, was devised by A. W. Dow of the Colprovia Asphalt Company. He took a sample of a densely-graded hot-mix pavement and agitated this sample in distilled water for varying lengths of time. If the mixture withstood the stripping through the final washing period the material was considered satisfactory. In 1928, Purdue University (10) desired to make a study of this subject in connection with the construction of low-cost surface treatment types of roads in which most of the aggregate used was between 3/4" - 1/8" in size, and liquid bituminous materials were used instead of the semi-solid asphalt cements which are used in hot-mix construction. They, therefore, modified the Dow Test to meet these conditions and it was this modification of the Dow Method that was used in this research. In preparing and testing bituminous mixtures, a 500 gram sample of each aggregate was weighed into a flat pan and coated by hand stirring with a predetermined amount of bitumen for thorough coating. Five percent by weight of all types of bitumen was used in most cases at standard temperatures for the application of each particular grade of bitumen. These samples were then allowed to air-cure for seven days at room temperature. After the completion of the curing period, each sample was placed in a two-quart Mason fruit jar and covered with 1,000 ml of distilled water. The coated aggregate was separated into individual particles by hand before being placed in the jar. The samples were then placed into a rack built to fit into a standard Ro-Tap sieve-shaker and agitated for thirty minutes at room temperature. A thorough and violent agitation of the water through the coated particles was accomplished by this method. After washing, the samples were allowed to dry on a laboratory table, rated by count and visual inspection to the amount of stripped particles, and rated as Excellent, no stripping; Fair, 0% - 25% stripping; and Poor, more than 25% stripping.

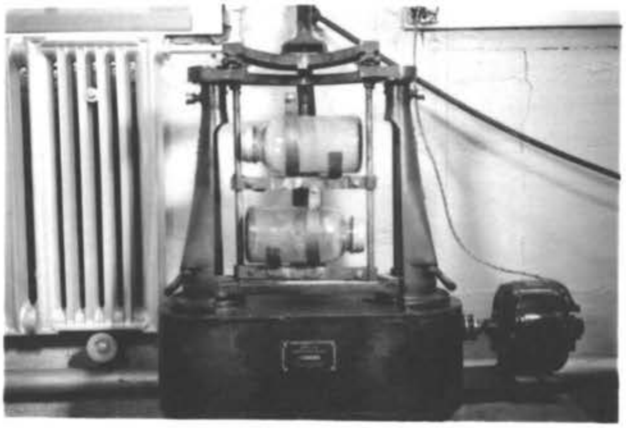

FIGURE 3

DOW TEST APPARATUS

FIGURE 4

SWELL TEST APPARATUS

FIGURE 5

TREMPER TEST APPARATUS

The Tremper Test

The second test selected was the method proposed by Mr. Bailey Tremper (9) of the Washington State Highway Department. By this test it is possible to determine the actual amount of stripping done by the water upon the aggregate. The test consists essentially of a method whereby the proportion of aggregate in a bituminous mixture from which the coating is stripped during agitation with water under controlled conditions may be determined. Quantitative determination of the percentage of stripped particles is made on the portion of the aggregate finer than the #100 mesh sieve. When the mixture after agitation is washed through a #100 mesh sieve, fine particles from which the bituminous coating has been stripped pass readily, while those on which the coating has been unchanged are retained. The test may be applied either as a measure of the adhesive characteristics of the aggregate or of the bituminous material. When testing bituminous materials, a standard sample should be prepared from aggregates upon which the coating is readily stripped. This sample will act as a check for other aggregates.

The aggregate used should be screened and recombined to the following grading:

Passing	Retained on	Percent Passing	Percent Retained
	¼" square		0
¼" square	No. 4 sieve	10	10
No. 4 sieve	No. 10 sieve	25	35
No. 10 sieve	No. 40 sieve	35	70
No. 40 sieve	No. 80 sieve	12	82
No. 80 sieve	No.100 sieve	0	82
No.100 sieve	No.200 sieve	6	88
No.200 sieve		12	100

Coarse aggregate is crushed and pulverized to obtain fractions to give the above grading.

A sample of the graded aggregate is warmed in an oven for six hours or more at a temperature of 130 to 140 F. Mixing with bituminous materials is started immediately after removal from the oven. The bituminous material is also warmed to a temperature in accordance with that used in construction work.

The warmed aggregate is placed in an earthenware bowl or porcelain mortar and the bituminous material is added in a quantity to result in a mixture of medium richness (5% - 8%). The mixture is stirred and rubbed vigorously with a large spoon until all of the particles of aggregate appear to be uniformly coated.

Each sample was prepared in 500 gram lots and after mixing was divided into 50 gram portions. All portions that were not tested immediately were set aside for further use. One of the samples of the mixture was placed in a

6 ounce can and floated on the surface of a water bath at 77 F for five minutes before testing to insure cooling to that temperature. It was then transferred to a 250 ml Erlenmeyer flask and 100 ml of distilled water at 77 F was added and the flask given a few brisk shakes.

This is to break up any large agglomerations of the mixture. By means of a burette clamp the flask was attached in a vertical position to the oscillating post of a Ro-Tap sieve shaker and it was agitated for a ten-minute period.

At the conclusion of the shaking period, the contents were washed through clean #40 and #100 mesh sieves (nested together loosely to allow the air to escape as the water flows through) by means of a fine spray of water, and the #100 minus solids were caught in the sieve pan. The wash water and suspended matter were transferred to a beaker. The heavier solids adhering to the pan were transferred with the aid of the water jet. A second washing was made, after which the water, this time containing no suspended matter, was decanted off, and the heavier sand particles transferred as above. The whole washing period and transferring procedure requires about seven minutes.

From 15 to 30 ml of a 10% sodium hydroxide solution was added to the contents of the beaker in order to flocculate the suspended matter. It has been found that 15 ml usually is sufficient, but occasionally as much as 30 ml is necessary to obtain a complete settlement within four hours.

After settling, a large portion of the clear water was decanted or siphoned off. The mixture was filtered through a tarred gooch crucible containing a thin asbestos matting. The filtered solids were washed with about 25 ml of benzol to remove adhering bitumen.

The crucible and contents were then dried to constant weight in an oven at 105 C. The weight of the material so recovered is expressed as a percentage of the weight of the aggregate finer than the #100 mesh sieve in the original 50 gram sample, and is designated as the "Loss in the Wash Test".

$$\% \text{ loss in Wash Test} = \frac{A}{B} \times 100$$

Where A = increase in weight of the gooch crucible

and B = weight of aggregate finer than the #100 mesh sieve in the original sample of mixture, or

$$B = \frac{0.18 \times 50}{1 + \frac{\% \text{ oil}}{100}}$$

Actually, this test is a modification of the Dow Wash Test, but it allows the investigator to determine the actual amount of stripping that takes place.

The Swell Test

The Swell Test was originally devised by the Arizona Highway Department (11) for use with the finer sized particles of aggregate, but it has acquired a more general importance through modifications by Hveem of the California Division of Highways. The improved swell test is made upon a compacted specimen of oil mixed aggregate representing typical proportions of bitumen as well as grading used in actual construction. In testing, the mixture is compacted in a cylindrical mold of 4 inches inside diameter, and 5 inches high; then a perforated disc 1/8" thick and 3 7/8" in diameter, with a 5 1/2" upright stem in its center is placed on top of the compacted mixture. The upright stem is in contact with an Ames dial which indicates the swelling of the mixture induced by 500 ml of water which is poured into the upper part of the mold on the surface of the specimen. Swell readings are taken after 24 hours and recorded in thousandths of an inch.

To secure a uniform grading of the aggregate for this test, the specification of the Oregon State Highway Commission for an open graded asphaltic concrete was used. Their specification for a Class C mixture was used with the following grading:

Passing	Retained on	Percent
3/8" sieve	1/4" sieve	40
1/4" sieve	No. 10 sieve	30
No. 10 sieve	No. 40 sieve	12
No. 40 sieve	No. 80 sieve	4.8
No. 80 sieve	No.200 sieve	4.8
No.200 sieve		2.4
Asphaltic content		6.0
		100.0

The aggregate was crushed, graded, and recombined to the above percentages. It was then heated in an oven for two hours at 105 C before the bitumen was added. The bitumen was heated to a temperature comparable with those used in actual construction use for a grade of that particular type. After the bitumen has been added to the aggregate, the mixture was stirred with a large spoon until all of the aggregate had received a uniform coating. As soon as the mixture had cooled, it was placed in the cylindrical mold and compacted in a testing machine at a pressure of 300 pounds per square inch. This pressure is comparable to that produced by a ten ton road roller. Before the mixture was removed from the testing machine, the mold was inverted and the mixture pushed through the mold to the other end and recompacted. This insures a smooth surface on the sample to be used in the test.

Compressive Method

In addition to the three tests described above, a method used in Germany was tried but discarded as it was not applicable with the softer grades of bitumen. This method used two-inch cubes of bituminous mixtures which were compacted at 300 pounds per square inch pressure. After compacting, one half of the cubes were allowed to cure in the air and the other half of the cubes were placed in a water bath at 77 F to cure. They were tested for compressive strength at 24 hours and 30 days. With the semi-solid grades of bitumen, this test should give excellent results, but the presence of the volatile materials in the bitumen of the softer grades made this test inapplicable as the samples cured in water disintegrated before they could be tested. The purpose of the test was to compare the difference in the compressive strengths of the air-cured and water-cured samples. However, this was impossible as the water-cured sample would not retain their shape in the bath and crumbled before they could be tested. If this test could have been used, it would have given an excellent check as the difference in the compressive strength of a bituminous mixture between the air-dry and water cured specimens would be interesting to investigate since they simulate actual conditions that are present in a mixture under actual use.

Sometimes laboratories have made tests of the stripping action of various aggregates, but they have employed only one grade of bitumen in the test. From the data received with an aggregate and one grade of bitumen, conclusions were then drawn concerning the behavior of any grade of bitumen with the aggregate in question. However, it is not possible to extend the data received from tests using only one grade to cover the entire range of bituminous products. If it is desired to use a certain grade of bitumen with an aggregate, that grade of bitumen must be used in testing the mixture for its resistance to stripping, rather than employing some other grade that may be on hand in the laboratory at the time of the test. Tremper, in describing his method, suggested the use of SC-2 to predict the behavior of an aggregate coated with bitumen in the presence of water. While the data obtained from such a test will indicate the resistance of the mixture to water, it will not give the same results if some other grade of bitumen is used. In fact, some aggregates would be rejected if the data of the mixing with SC-2 were taken to indicate the reaction of the aggregate with any bitumen, while some other grades of asphalt might give values indicating excellent resistance to the stripping of the film from the aggregate.

Chapter IV

DISCUSSION OF RESULTS

Hydrophilic Aggregate Effect

It has been generally agreed by all authorities in the field of bituminous research that hydrophilic, water-loving, aggregates should not be used for construction purposes. If the aggregate has a greater affinity for water than for the bitumen used to coat it, care should be taken to avoid the use of this type of aggregate. From previous investigations (10) it has been proved that granites, syenites, quartz, and all other highly silicious aggregates will be hydrophilic in character and these materials should not be used if it is possible to use other aggregate. On the other hand, basalts, trap rock, limestones, dolomites, and blast furnace slag have been classified as hydrophobic, water-repelling aggregates and suitable for use.

Oregon Aggregates

In the State of Oregon some of these aggregates do not exist for use in construction work. Basalt is the main type of aggregate available and most of the other types used are also of igneous origin. As basalt is hydrophobic in character, the principal problem is the selection of a bitumen that will give the best adhesive values. However, no general statement can be made in which it may be said that any one grade of bitumen will be better than all of the rest. Certain types of basalt will adhere better to RC-4 than to any other grade, while another aggregate that is still classed as a basalt will give higher values with MC-2 or SC-6. The only way of determining the grade of bitumen to use is by actually subjecting the aggregate to tests for the resistance to stripping with each grade of bitumen. Of course, the method of application of the bitumen to the aggregate will govern. However, it is foolish to use an SC-2 in a road-mix with an aggregate where it has been proved that SC-2 will not give the necessary adhesion but that the use of an SC-6 in a penetration macadam will produce a satisfactory mat. The selection of a bitumen should be made with care to develop the greatest adhesion and the greatest resistance to the stripping of the bitumen from the aggregate by the action of water.

Inasmuch as all of the aggregates used in this research were obtained from sources within the State of Oregon, all of the discussion in this paper must be confined to the reactions between these native minerals and the grades of bitumens normally used in this state. If a larger number of aggregates had been used in the research, more general conclusions might have been reached.

The State of Oregon is peculiarly fortunate in the types of mineral aggregate within its borders. Most of the rock is of igneous origin and well distributed throughout the state. Basalt is the predominant mineral, with gabbro, andesite, rhyolite, and felsite also available. The sedimentary rocks are in a minority and outside of a few localities are not considered for construction purposes. Metamorphic aggregates are available, but they occupy the same position as the sedimentary minerals and are not classed as a major material. Of course, there are many other types of mineral aggregate scattered throughout the state, but care is taken to avoid the use of materials other than those which are known to produce consistently excellent results when used. However, there are times when the only economic source of material may not be of the basaltic or gabbro type of aggregate. In this case care must be taken to determine the reaction of the mineral in question with the various grades of bitumen. This is especially true where the mineral may be of a serpentinic nature. Serpentine is definitely hydrophilic and its use should be avoided.

Most igneous materials are hydrophobic, but this can not be stated as being true in all cases. No two minerals possess the same adhesive qualities. It is necessary to test the reactions between each aggregate and the bitumen before any definite conclusions may be reached concerning the two materials.

As basalts are the most prevalent type of aggregate within the state, most of the rock tested was of this material. They were selected from all parts of the state as being representative of this class of mineral. The felsite and the rhyolites are found in the eastern part of the state, and they are typical of their classes. The gabbros came from the Coast Mountains in the northwestern corner of the state where they are classed as the best material available in that region. The serpentine sample came from the Coast Mountains. While the deposits of this mineral are not extensive, sometimes they may be used and their reactions with the bituminous materials known. The granite came from the Siskyou Mountains on the California border.

As basalts and gabbros came from the same volcanic origin, their composition is identical and their behavior in the tests was also in agreement. All of these minerals gave fairly consistent results and they may be classed as hydrophobic.

The rhyolites from the eastern part of the state gave almost as good results in the Dow and the Tremper methods except for the SC-2 and the MC-2 tests. In the Dow Test, the SC-2 mixture showed a large amount of stripping that was not indicated in the Tremper Test. On sample 15, the MC-2 mixture in the Tremper Test gave very poor results until the thirty day test was reached. From that period onward the stripping dropped to a very low figure, comparing very well with the other grades of bitumen. Little was learned from the study of the data obtained by the Swell Test. The readings were so erratic that a comparison was almost impossible.

Granite has always been considered as definitely hydrophilic, both from laboratory tests and actual use in bituminous mixes. Although it is not used to any appreciable extent in Oregon, many states have little other material and they are forced to use this mineral. The Dow and the Swell tests indicated this tendency quite clearly, but the Tremper Test showed it only with the SC-2 and the MC-2 mixtures. The mixtures of this mineral with RT-8, RC-4, and SC-6 gave fairly low losses in adhesion throughout the test period, although the hydrophilic tendency was indicated by the ten day sample that had been placed in water for twenty-four hours. While the losses on these samples would not reject the mixes, they were greater than the average adhesion loss increase for other aggregates. However, the sixty day tests showed that all of the bitumens used had increased their adhesional values so any of them would be acceptable for use.

The felsite sample came from the southeastern portion of the state. All three of the tests showed it to be hydrophobic except the SC-2 test by the Tremper Method, where the mineral showed a slight tendency towards the hydrophilic after being soaked in water. In the Swell Test all of the mixes with this aggregate gave such small swells they were almost unreadable.

The control sample for the research was a sample of aggregate from Rose Lodge on the Salmon River Highway in the Coast Range. This mineral had been used to surface thirteen miles of highway in a penetration coat using RC-3 asphalt. After the mat had been in place for two weeks, it failed when a heavy rain occurred. The mineral was a serpentine although it closely resembled basalt. All three of the tests showed it to be highly hydrophilic although the thirty day samples in the Tremper Test gave acceptable results. In general though this mineral would have been rejected by any test used to indicate its adhesional ability.

Sample number 8, from the Coastal regions, was a mixture of basalts, gabbros, limestones, granite, and quartzites. It was listed on the data sheets as a gravel since there was no predominant mineral. With this aggregate the tests did not agree. The Dow Test showed it to be hydrophilic with all grades of bitumen except MC-2 which was rated as fair, the Swell Test gave uniform readings with a moderate amount of swell; the Tremper Test showed RT-8, SC-6, and SC-2 as giving excellent adhesion, RC-4 as moderate, and MC-2 as poor. The only explanation for these erratic readings may be that the composition of the gravel in each sample was not the same, which would tend to give different values of stripping in each case.

Only one aggregate of the sedimentary type was used in this research as the available supply of this type of material in Oregon is scarce. Limestone and sandstone are also available in certain localities but they are not used. The sandstone is too soft and will not pass the abrasion test, and the limestone is used mainly in the production of lime and cement.

The shale sample in general proved to be moderately hydrophobic. While its readings in the Dow Test were Poor for most grades of bitumen, the Swell Test and the Tremper Test showed it to be fairly resistant to stripping with SC-2 and MC-2 the only grades of bitumen giving high losses.

Resistance of Bitumens to Stripping

In the comparison of the different grades of bitumen, the RT-8 and the RC-4 gave the most consistent results with all of the aggregates as well as being the most resistant to the stripping action. Both of these materials have greater asphaltene content than any of the other grades of bitumen, which would tend to indicate that the asphaltene content is the main determining factor in the adhesion of the bitumen to the aggregate. In addition, these grades of bitumen contain solvents which are quite volatile. The RT-8 contains napthalene and the RC-4 contains naptha. These solvents may aid the adhesion of the bitumens by cutting the air film surrounding the aggregate. Usually, the solvents in the bitumen would evaporate, leaving the bitumen coating the aggregate, but it is possible that some of the solvents would penetrate into the pores of the mineral, displacing the air film allowing the heavier constituents in the bitumen to adhere to the surface of the aggregate. In this manner, it may be said that the solvents "wet" the surface of the stone ahead of the rest of the bitumen and are then replaced by the non-volatile material.

The SC-6 and the SC-2 do not contain volatile solvents, but are cut back with residual oils to the desired consistency. These residual oils remain in the bitumen and do not evaporate like the volatile solvents. For this reason, the percentage of asphaltenes in the bitumen of these grades will be less than in the cutbacks containing the more volatile solvents. While the residual oils will have a lower surface tension than the residue, they will not cut the air film as easily as the solvents and will not aid the heavier portions of the bitumen in adhering as readily. If sufficient time is given the bitumens of these grades, they will penetrate the layer of air surrounding the aggregate and develop the maximum available adhesion. Of course, this will take time and the data from the Tremper Method shows this period to be about thirty days before the maximum adhesion is developed. If the aggregate is the least susceptible to the stripping action, the presence of water during the period in which the bitumen is developing its maximum adhesion will force the bitumen away from the aggregate. All tests showing adhesion losses of more than two or three percent showed this to be true. For example, the mixture of SC-2 and the gabbro sample number 6 showed a loss of 18.45 percent for the first day, 12.22 percent at seven days, and 5.07 percent after sixty days. In nearly all cases, if sufficient time is given the bitumen to develop its full adhesive values with the aggregate, little trouble may be expected from the action of stripping.

The MC-2 grade contains a solvent, kerosene, but the asphaltene content is low. This grade gave very erratic results in all tests. The solvent seemed to aid the initial adhesion of the bitumen, but the low percentage of asphaltenes prevented the development of adhesion that should be expected. With aggregate sample number 6, the initial test showed a loss of 9.13 percent and the sixty day test showed 6.96 percent. In other cases, this bitumen gave comparable results with the other grades.

The asphalts coming from the same field should react alike. As they do not, the only possible reason for their unlike behavior must be in the asphaltene content and the type of material used to cutback the asphalt to the desired consistency. The volatile solvents are used as they are designed to evaporate from the bitumen leaving the heavier asphalts to coat the aggregate. The non-volatile solvents do not evaporate from the bitumen, but they keep the asphalts fluid, allowing them to flow into the interstices of the aggregate they coat. This is an advantage under most conditions, but it can be a detriment if the aggregate is hydrophilic and water is present. As the slower curing asphalts will not have time to develop their adhesion, the water will penetrate to the aggregate, stripping the asphalt.

The RT-8 bitumen is a tar produced from petroleum residue by a cracking process. In the cracking of this residue to produce heating gas the tar is obtained. It differs from the asphalts as the aliphatic chains have been converted into other products. This produces a heavier molecule containing a high percentage of aromatic compounds. The specific gravity of the tar is greater than that of water, and this aids the tar in displacing the water surrounding the aggregate to be coated. The aromatic compounds present in the tar are unsaturated compounds and they are capable of combining with the oxygen in the air. When the tar comes into contact with the air film surrounding the bitumen, the aromatic character of the material, aided by its high specific gravity, will absorb the oxygen from the air allowing the tar to penetrate directly to the surface of the aggregate and to develop its adhesion in a shorter time than one of the asphalts could. This higher primary adhesion aids the tar in resisting the action of the water that might happen to be present. The uniformly excellent resistance of this material to stripping indicates the advisability of using this bitumen if any doubt exists over the hydrophobic properties of the aggregate.

Comparison of Testing Methods

In the comparison of the three methods used to determine the resistance of the bitumens and aggregates to the stripping action, the tests were first checked with an aggregate of known hydrophilic tendencies to prove their suitability in determining the adhesional loss in the bituminous mixtures. All three of the methods proved themselves acceptable by showing that the serpentine from Rose Lodge was definitely hydrophilic. Therefore, the principle factor to be considered in comparing these tests is the advantage they possess for control work on the bituminous mixes. All are of the accelerated type and may be used to determine the stripping resistance of a mix in a period of seven days or less. The Dow Test requires seven days for the solvent in the bitumen to evaporate before testing the mixture, but the Tremper Test and the Swell Test may be run as soon as the bitumen has been mixed with the aggregate.

The preparation of the aggregates for the testing of the bituminous mix is essentially the same for all three of the tests. The Tremper and the Swell tests use graded aggregates, while the Dow Test uses aggregates of one selected size. They are heated and the bitumen added in the same manner.

In testing the mixes, the Dow Test takes a shorter period of time than either of the other two, as the mixture is merely crumbled into a jar and agitated in the Ro-Tap shaker. The results are obtained by visual inspection as soon as the test is completed. The main disadvantages of this test are the length of curing time required, seven days, and the manner of rating the stripping that occurred.

The Tremper Test allows the mixtures to be tested as soon as they are mixed, but the filtering and settling of the filtrate requires at least four hours. The filtering and drying of this residue through the Gooch crucible requires an additional two hours. Usually this requires a total time of two days before the data is obtained. However, the exact percentage of the adhesion loss is determined, giving greater accuracy than the data from the Dow Test.

The Swell Test requires the compacting of the mixture in a cylindrical mold before testing which requires one or two hours time after mixing. This time lapse is necessary to allow the mix to cool to room temperature. After the introduction of the water to the test mold, a twenty-four hour period is required before the readings may be taken. In theory, this method should give excellent results, but the swells occurring in the mixes containing the softer grades of bitumen do not compare with the stripping losses found by either the Tremper or the Dow methods. In view of this fact, the writer would hesitate to recommend the use of this method when asphalts containing non-volatile oils are being tested for their resistance to stripping.

In considering the advantages and disadvantages of each of the three methods used in this research problem, it is the opinion of the writer that the Tremper Method gives the clearest and most accurate picture of the reaction between the aggregate and the bitumen. All three of these methods have been used throughout the United States in measuring the resistance of the bituminous mixtures to the stripping action, but no comparison of the relative values of each of the three methods using the same aggregates and grades of bitumen has been presented. With the presentation of this paper, it is hoped that the knowledge of the comparative values between the various types of aggregate and the different grades of bitumen available for use in highway construction work may be increased.

TABLE I

DOW WASH TEST

Adhesion of various grades of bitumen to aggregate

No.	Location	Aggregate	RT-8	RC-4	SC-6	SC-2	MC-2
1	Salem	Basalt	F	F	F	F	F
2	Corvallis	Basalt	F	F	F	F	E
3	Summit	Gabbro	E	E	E	E	E
4	Lakeview	Shale	F	P	P	P	F
5	Harper	Basalt	E	P	F	F	F
6	Nehalem	Gabbro	E	F	E	E	E
7	Gales Cr.	Basalt	F	E	F	F	F
8	Humbug Mt.	Gravel	P	P	P	P	F
9	Euchre Cr.	Basalt	E	E	E	F	F
10	Ashland	Granite	P	P	P	P	P
11	Burns	Rhyolite	F	F	F	P	F
12	Rose Lodge	Serpentine	P	P	P	P	P
13	Summit	Basalt	F	F	F	P	P
14	Valley Falls	Felsite	F	F	F	P	P
15	Gap Ranch	Rhyolite	F	F	F	P	F

Bitumens: RT-8, RC-4, SC-6, SC-2, MC-2

Aggregates: As noted above

Curing time: Seven days

Condition of aggregate: Heated, oven dry

Amount of bitumen: Five percent by weight

TABLE 2

TREMPER METHOD

Aggregate Sample No. 1

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	2.15	2.18	0.96	14.55	8.65
4	2.05	2.31	1.25	6.68	4.96
7	1.87	2.22	1.47	13.03	7.69
10	2.56	3.14	1.37	8.71	3.29
10W	5.41	7.49	3.25	21.05	25.20
30	1.53	2.68	1.66	7.55	1.86
60	1.29	2.15	1.21	7.23	1.53

Aggregate Sample No. 2

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	2.12	1.00	2.42	13.62	5.78
4	1.87	1.03	1.12	7.47	5.02
7	2.06	1.47	2.45	9.84	8.46
10	2.44	1.46	3.79	8.22	5.32
10W	5.91	3.18	5.30	19.96	9.25
30	2.11	1.77	2.23	8.23	3.43
60	1.56	1.05	1.97	7.84	2.78

TABLE 2(CONT)

TREMPER METHOD

Aggregate Sample No. 3

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	1.08	1.22	2.77	14.71	9.48
4	1.02	1.16	2.43	9.62	7.23
7	1.24	1.08	2.51	9.80	6.74
10	1.19	1.20	1.99	7.27	6.91
10W	3.02	2.36	3.65	13.84	13.02
30	1.21	1.03	1.82	5.77	5.86

Aggregate Sample No. 4

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	6.29	7.61	8.43	29.81	20.77
4	5.91	5.42	7.97	27.67	17.43
7	5.27	5.03	8.24	28.14	15.65
10	6.04	4.97	7.14	19.32	17.06
10W	10.56	10.22	17.66	41.64	32.90
30	4.62	4.32	5.29	15.16	14.08
60	4.06	3.91	4.82	11.47	12.82

TABLE 2(CONT)

TREMPER METHOD

Aggregate Sample No.5

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	1.87	2.26	1.92	16.00	8.07
4	2.94	2.25	3.34	13.18	2.61
7	2.12	1.89	1.43	32.20	2.00
10	2.51	2.82	4.06	58.95	3.31
10W	5.65	7.35	5.01	100.00	12.70
30	2.36	2.32	2.44	18.05	2.30
60	2.18	2.14	1.92	3.34	1.77

Aggregate Sample No. 6

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	4.81	5.82	6.21	18.45	9.13
4	4.24	5.46	5.86	11.15	7.63
7	4.67	4.91	5.79	12.22	8.14
10	3.96	5.06	5.21	9.80	7.56
10W	7.57	9.72	10.13	15.95	15.22
30	3.78	4.83	4.88	6.12	7.08
60	3.52	4.56	4.62	5.07	6.96

TABLE 2(CONT)

TREMPER METHOD

Aggregate Sample No.7

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	1.21	1.35	0.87	18.70	1.51
4	1.33	0.78	1.23	13.60	1.82
7	2.16	1.65	0.51	15.30	0.61
10	2.23	2.02	0.68	12.80	1.12
10W	4.01	5.02	1.18	42.60	3.10
30	1.32	1.81	1.13	8.50	1.03
60	1.18	1.36	1.02	2.40	0.86

Aggregate Sample No.8

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	1.22	13.41	1.58	10.62	44.85
4	2.86	17.20	1.01	10.15	47.30
7	1.32	16.78	2.68	5.39	29.90
10	2.14	11.90	1.01	4.86	25.35
1CW	4.00	16.90	4.04	8.48	70.90
30	1.25	10.82	1.56	2.77	13.80
60	1.18	10.21	1.43	1.60	11.27

TABLE 2(CONT)

Aggregate Sample No.9

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	1.08	1.21	0.84	4.26	5.82
4	1.15	1.18	1.01	3.92	4.76
7	1.03	1.46	0.95	3.14	4.21
10	1.01	1.24	0.96	2.32	4.37
10W	1.96	2.47	2.02	5.69	6.18
30	1.12	1.43	1.04	1.24	2.22
60	1.07	1.18	0.98	1.15	1.81

Aggregate Sample No.10

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	1.37	1.42	3.24	35.49	17.20
4	2.22	2.46	2.68	22.85	11.44
7	2.15	2.41	3.37	30.95	13.32
10	2.03	1.88	2.72	17.90	12.72
10W	8.61	7.78	9.82	30.40	29.65
30	1.43	1.51	2.39	5.65	8.42
60	1.08	1.24	1.86	4.02	5.36

TABLE 2(CONT)

TREMPER METHOD

Aggregate Sample No.11

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	3.56	4.59	9.23	32.20	18.13
4	3.63	4.48	8.11	19.77	12.92
7	3.21	4.96	7.82	12.31	14.64
10	3.13	4.82	7.63	13.61	11.86
10W	5.34	7.67	14.74	21.20	25.25
30	3.22	4.32	7.75	11.60	13.62
60	2.96	4.15	7.02	11.33	13.03

Aggregate Sample No.12

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	22.36	15.60	66.50	43.90	87.10
4	19.74	12.95	40.40	17.00	41.25
7	16.32	11.45	41.90	29.70	19.70
10	21.49	17.60	52.40	22.30	52.80
10W	33.42	18.18	83.50	49.70	90.00
30	17.37	12.15	26.10	21.62	56.80
60	16.17	11.76	24.72	16.28	42.64

TABLE 2(CONT)

TREMPER METHOD

Aggregate Sample No.13

Adhesion Loss in Per Cent

Curing time vs Grade of Bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	3.14	3.31	5.16	2.88	6.13
4	3.02	2.87	3.37	2.84	4.46
7	4.21	4.87	4.89	3.61	4.68
10	3.25	3.40	4.28	2.88	5.38
10W	5.55	5.72	4.57	4.82	5.68
30	3.07	3.15	2.18	2.61	2.94
60	2.61	5.10	2.06	2.57	2.77

Aggregate Sample No.14

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	2.68	1.68	11.30	32.10	16.82
4	2.72	1.65	7.52	25.60	10.10
7	3.11	2.07	6.81	13.16	15.30
10	2.42	2.34	5.85	14.75	8.58
10W	3.92	4.00	14.38	71.90	24.60
30	2.37	1.55	5.62	14.40	9.52
60	1.87	1.24	5.32	14.13	8.78

TABLE 2(CONT)

TREMPER METHOD

Aggregate Sample No.15

Adhesion Loss in Per Cent

Curing time vs Grade of bitumen

Days	RT-8	RC-4	SC-6	SC-2	MC-2
0	5.46	9.35	10.35	23.70	57.90
4	6.72	10.30	16.05	13.25	60.80
7	7.86	9.25	10.35	27.35	52.80
10	5.31	9.15	4.84	14.80	67.30
10W	11.39	18.08	13.65	59.60	72.60
30	5.83	8.75	4.23	11.90	5.62
60	5.14	8.14	3.62	11.28	4.91

TABLE 3

TREMPER METHOD WITH RT-8 BITUMEN

No.	Location	Aggregate	Percent of adhesion loss at various days						
			0	4	7	10	10W	30	60
1	Salem	Basalt	2.15	2.05	1.87	2.56	5.41	1.53	1.29
2	Corvallis	Basalt	2.12	1.87	2.06	2.44	5.91	2.11	1.56
3	Summit	Gabbro	1.08	1.02	1.24	1.19	3.02	1.21	1.18
4	Lakeview	Shale	6.29	5.91	5.27	6.04	10.22	4.62	3.91
5	Harper	Basalt	1.97	2.94	2.12	2.51	5.65	2.36	2.18
6	Nehalem	Gabbro	4.31	4.24	4.67	3.96	7.57	3.78	3.52
7	Gales Cr.	Basalt	1.21	1.33	2.16	2.23	4.01	1.32	1.18
8	Humbug Mt.	Gravel	1.22	2.86	1.32	2.14	4.00	1.25	1.24
9	Euchre Cr.	Basalt	1.08	1.15	1.03	1.01	1.96	1.12	1.07
10	Ashland	Granite	1.37	2.22	2.15	2.03	8.61	1.43	1.08
11	Burns	Rhyolite	3.56	3.63	3.21	3.13	5.34	3.22	2.96
12	Rose Lodge	Serpentine	22.36	19.74	16.32	21.49	33.42	17.37	16.17
13	Summit	Basalt	3.14	3.02	4.21	3.25	5.55	3.07	2.61
14	Valley Falls	Felsite	2.68	2.72	3.11	2.42	3.92	2.37	1.86
15	Gap Ranch	Rhyolite	5.46	6.72	7.86	5.31	11.39	5.83	5.14

TABLE 3(CONT)

TREMPER METHOD WITH RC-4 BITUMEN

No.	Location	Aggregate	Percent of adhesion loss at various days						
			0	4	7	10	10W	30	60
1	Salem	Basalt	2.18	2.31	2.22	3.14	7.49	2.68	2.15
2	Corvallis	Basalt	1.00	1.03	1.47	1.46	3.18	1.77	1.05
3	Summit	Gabbro	1.22	1.16	1.08	1.20	2.36	1.03	0.96
4	Lakeview	Shale	7.61	5.42	5.03	4.97	10.56	4.32	4.06
5	Harper	Basalt	2.25	1.89	2.32	2.26	7.35	2.32	2.14
6	Nehalem	Gabbro	5.82	5.46	4.91	5.06	9.72	4.83	4.56
7	Gales Cr.	Basalt	1.35	0.78	1.65	2.02	5.02	1.81	1.36
8	Humbug Mt.	Gravel	13.41	17.20	16.78	11.90	16.90	10.82	10.21
9	Euchre Cr.	Basalt	1.21	1.18	1.46	1.24	2.47	1.43	1.18
10	Ashland	Granite	1.42	2.46	2.41	1.88	7.78	1.51	1.24
11	Burns	Rhyolite	4.59	4.48	4.96	4.82	7.67	4.32	4.15
12	Rose Lodge	Serpentine	15.60	12.95	11.45	17.60	18.18	12.15	11.76
13	Summit	Basalt	3.31	2.87	4.87	3.40	5.72	3.15	5.10
14	Valley Falls	Felsite	1.68	1.65	2.07	2.34	4.00	1.55	1.24
15	Gap Ranch	Rhyolite	9.35	10.30	9.25	9.15	18.08	8.75	8.14

TABLE 3(CONT)

TREMPER METHOD WITH SC-6 BITUMEN

No.	Location	Aggregate	Percent of adhesion loss at various days						
			0	4	7	10	10W	30	60
1	Salem	Basalt	0.96	1.25	1.47	1.37	3.25	1.66	1.21
2	Corvallis	Basalt	2.42	1.12	2.45	3.79	5.30	2.23	1.97
3	Summit	Gabbro	2.77	2.43	2.51	1.99	3.65	1.82	1.62
4	Lakeview	Shale	8.43	7.97	8.24	7.14	17.66	5.29	4.82
5	Harper	Basalt	1.92	3.34	1.43	4.06	5.01	2.44	1.92
6	Nehalem	Gabbro	6.21	5.86	5.79	5.21	10.13	4.88	4.62
7	Gales Cr.	Basalt	0.87	1.23	0.51	0.68	1.18	1.13	1.02
8	Humbug Mt.	Gravel	1.58	3.14	1.01	2.68	4.04	1.56	1.43
9	Euchre Cr.	Basalt	0.84	1.01	0.95	0.96	2.02	1.04	0.98
10	Ashland	Granite	3.24	2.68	3.37	2.72	9.82	2.39	1.86
11	Burns	Rhyolite	9.23	8.11	7.82	7.63	14.74	7.75	7.02
12	Rose Lodge	Serpentine	66.50	40.40	41.90	52.40	83.50	26.10	24.72
13	Summit	Basalt	5.16	3.37	4.89	4.28	4.57	2.18	2.06
14	ValleyFalls	Felsite	11.30	7.52	6.81	5.84	14.38	5.62	5.31
15	Gap Ranch	Rhyolite	10.25	16.05	10.35	4.84	13.65	4.23	3.62

TABLE 3(CONT)

TREMPER METHOD WITH SC-2 BITUMEN

No.	Location	Aggregate	Percent of adhesion loss at various days 0	4	7	10	10W	30	60
1	Salem	Basalt	14.55	6.68	13.03	8.71	21.05	7.55	7.23
2	Corvallis	Basalt	13.62	7.47	9.33	8.22	19.96	8.23	7.84
3	Summit	Gabbro	14.71	9.62	9.80	7.27	13.84	5.77	4.17
4	Lakeview	Shale	29.81	27.67	28.14	19.32	41.64	15.16	11.47
5	Harper	Basalt	16.00	13.18	32.20	58.95	100.00	18.05	3.34
6	Nehalem	Gabbro	18.45	11.15	12.22	9.80	15.95	6.12	5.07
7	Gales Cr.	Basalt	18.70	13.60	15.30	12.80	42.60	8.50	2.40
8	Humbug Mt.	Gravel	10.62	10.15	5.39	4.86	8.48	2.77	1.60
9	Euchre Cr.	Basalt	4.26	3.92	3.14	2.32	5.69	1.24	1.15
10	Ashland	Granite	35.49	22.85	30.95	17.90	30.40	5.65	4.02
11	Burns	Rhyolite	32.20	19.77	12.31	13.61	21.20	11.60	11.33
12	Rose Lodge	Serpentine	43.90	17.00	29.70	22.30	49.70	21.62	16.28
13	Summit	Basalt	2.88	2.84	3.61	2.88	4.32	2.61	2.57
14	ValleyFalls	Felsite	32.10	25.60	13.16	14.75	71.90	14.40	14.13
15	Gap Ranch	Rhyolite	23.70	13.25	27.35	14.80	59.60	11.90	11.28

TABLE 3(CONT)

TREMPER METHOD WITH MC-2 BITUMEN

No.	Location	Aggregate	Percent of adhesion loss at various days						
			0	4	7	10	10W	30	60
1	Salem	Basalt	8.65	4.96	7.69	3.29	25.20	1.86	1.53
2	Corvallis	Basalt	5.78	5.02	8.46	5.32	9.25	3.43	2.78
3	Summit	Gabbro	9.48	7.23	6.74	6.91	13.02	5.86	5.24
4	Lakeview	Shale	20.77	17.43	15.65	17.06	32.90	14.08	12.82
5	Harper	Basalt	8.07	2.61	2.00	3.31	12.70	2.30	1.77
6	Nehalem	Gabbro	9.13	7.63	8.14	7.56	15.22	7.08	6.96
7	Gales Cr.	Basalt	1.51	1.82	0.61	1.12	3.10	1.03	0.86
8	Humbug Mt.	Gravel	44.85	47.30	29.90	25.35	70.90	13.80	11.27
9	Euchre Cr.	Basalt	5.82	4.76	4.21	4.37	6.18	2.22	1.18
10	Ashland	Granite	18.13	12.92	14.64	11.86	25.25	13.62	13.03
11	Burns	Rhyolite	17.20	11.44	13.32	12.72	29.65	8.42	5.36
12	Rose Lodge	Serpentine	87.10	41.25	19.70	52.80	90.00	56.80	42.64
13	Summit	Basalt	6.13	4.46	4.68	5.38	5.68	2.94	2.77
14	Valley Falls	Felsite	16.82	10.10	15.30	8.58	24.60	9.52	8.78
15	Gap Ranch	Rhyolite	57.90	60.80	52.80	67.30	72.60	5.62	4.91

TABLE 4

SWELL TEST

Swell produced in various Bituminous Mixtures

No.	Location	Aggregate	RT-8	RC-4	SC-6	SC-2	MC-2
1	Salem	Basalt	0.0035	0.0025	0.0022	0.0040	0.0041
2	Corvallis	Basalt	0.0022	0.0022	0.0005	0.0020	0.0025
3	Summit	Gabbro	0.0062	0.0021	0.0030	0.0040	0.0052
4	Lakeview	Shale	0.0072	0.0082	0.0078	0.0096	0.0104
5	Harper	Basalt	0.0023	0.0002	0.0025	0.0098	0.0082
6	Nehalem	Gabbro	0.0020	0.0018	0.0015	0.0025	0.0020
7	Gales Cr.	Basalt	0.0012	0.0005	0.0020	0.0040	0.0021
8	Humbug Mt.	Gravel	0.0035	0.0015	0.0034	0.0048	0.0042
9	Euchre Cr.	Basalt	0.0016	0.0012	0.0015	0.0023	0.0025
10	Ashland	Granite	0.0142	0.0121	0.0104	0.0172	0.0186
11	Burns	Rhyolite	0.0065	0.0045	0.0062	0.0078	0.0050
12	Rose Lodge	Serp'tine	0.0358	0.0494	0.0690	0.0420	0.0220
13	Summit	Basalt	0.0055	0.0060	0.0040	0.0158	0.0082
14	Valley Falls	Felsite	0.0007	0.0003	0.0006	0.0008	0.0001
15	Gap Ranch	Rhyolite	0.0023	0.0020	0.0004	0.0115	0.0010

Bitumens: RT-8,RC-4,SC-6,SC-2,MC-2

Amount of bitumen used in mix: Five per cent by weight

Aggregates: As noted above

Condition of aggregate when mixed: Oven dry, heated

Type of mix: Class C, Oregon State Highway Dept. Standards

All values of swell recorded in inches

Chapter V

CONCLUSIONS

In summarizing the conclusions drawn from the data obtained in this research, the following statements are the author's opinion and apply only to the types of aggregates, the grades of bitumen, and the methods of testing employed.

(1) Little more than the relative behavior of the resistance to the stripping action of water by a bituminous mixture may be gained if some other grade of bitumen, other than that in question, is used in the test.

(2) The use of a definitely hydrophilic aggregate should be avoided if possible. However, a bituminous mixture containing this type of aggregate will eventually become hydrophobic in character if sufficient time is given the bitumen to develop its full adhesion before water is allowed to come into contact with the materials. This period is usually not less than thirty days.

(3) Although most igneous aggregates are hydrophobic, care must be taken to use a grade of bitumen that will develop sufficient adhesion to resist the action of water upon the mixture.

(4) Aggregates containing Serpentinic material should be avoided as they are highly hydrophilic.

(5) The greatest resistance to the stripping action was developed by the RT-8 and the RC-4 grades of bitumen.

(6) The SC-6 grade of bitumen gave fairly good results although it did not develop the adhesion of the two above-mentioned grades.

(7) The SC-2 and the MC-2 grades of bitumen exhibited the greatest adhesional loss of all the grades tested.

(8) The Tremper Test gave the most accurate results of all the methods used in this research. In addition, this method required less time to run than either of the two other methods employed.

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