# A SIMPLIFIED METHOD OF MEASURING THE SURFACE TENSION OF ASPHALTIC OILS AND COMPARATIVE TESTS OF THEIR BONDING PROPERTIES

Thesis for the Degree of B. S.

William H. Smith

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# A SIMPLIFIED METHOD OF MEASURING THE SURFACE TENSION OF ASPHALTIC OILS AND COMPARATIVE TESTS OF THEIR BONDING PROPERTIES

A Thesis Submitted to

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by

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I

## FOREWORD

In preparing this thesis the author wishes to acknowledge the helpful criticisms and hints that were given by Professor E.A. Finney of the Civil Engineering Department of Michigan State College, and T. Wolenyneki, the laboratory assistant of Michigan State Highway Department, also to acknowledge indebtedness to the Civil Engineering Department and the Michigan State Highway Department for the use of the apparatus and materials, without which, this work could not have been completed.

## II

## INTRODUCTION

Within recent years the application of asphaltic oils to the improvement and construction of roads and highways has become one of the foremost industries of this country. Although up to the present time there has been very little direct research carried on with the sole purpose of determining the properties or conditions which help these oils become more efficient in their application to the roads, it is my belief that in order to have an efficient road oil certain important bituminous properties must be present. Since there are numerous methods of changing these properties, it is possible that oils may be comparatively improved by a simple change in any one or more of these properties. However, it will not be the purpose of this thesis to find out the changes that may be made, but its purpose is to determine some of these properties and simple methods of measuring them. The proper changes and methods are left for later research work.

In their research reports, A.R. Lee (1) and G. Mack (2) stress the important energy relations between asphalts and aggregates. They state that these relations, energy of adhesion, interfacial energy, and spreading coefficients of the oils with aggregates, was, are with slight variations, in proportion to the surface tension of the asphalts and aggregates. Assuming that these relations are true, it is the purpose of this thesis to devise a simple means of determining the surface tension of asphalts and to test the asphalts to see if certain properties shown by the energy relations may not somehow

predict the conditions that will be present when the oils are used in a mix with the tested aggregates.

Throughout this thesis, the words asphaltic oils, asphalts, and oils, will be used interchangeably to mean the same thing.

Since the surface tension of liquids is very important in this thesis, I believe a definition of Surface Tension is well in order.

By the Molecular Theory of Matter, each molecule within a liquid attracts and is attracted by surrounding molecules. Each molecule may thus be pictured as surrounded by a sphere of attraction. Forces then exist between each molecule and other molecules within its sphere of attraction. In the body of a liquid the resultant of these forces is zero, since each molecule is completely surrounded by similar molecules; in the surface layer this does not hold, as the molecules in the upper half of the sphere of attraction are comparatively few. Consequently, the free surface of a liquid behaves as if it were in a state of stress. Forces act across the surface which are the direct result of molecular attraction and consequently their measurement is of importance. If a straight line 1 cm. in length is drawn in the surface of the liquid in contact only with its own vapor, then the force across this line at right angles is defined as the Surface Tension of the liquid. Surface Tension is thus force per unit length. - (Physico-Chemical Methods - Reilly. Pg. 335)

Up to the present due to their various degrees of tenacity and natural color, there has not been devised a simple means of determining the surface tension of asphaltic oils. Of the various ways which the surface tension has been determined the one most applicable to general practice is given by C. Mack. (2)

He suspends a thread of asphalt having a known radius and length under conditions where only the forces of gravity and surface tension may act on it. After a certain length of time the action of gravity and surface tension are rated and through compilation of certain data on several strings of asphalt, he is able to determine the surface tension of the oil. There is only one serious objection to this method, namely, it can be applied only to asphalts which flow under the influence of gravitational forces. One of the somewhat less serious objections is the necessary time consuming operation of accurately measuring the radius of the thread.

The simple method I propose to be used hereafter is based on DuNouys Ring method of obtaining surface tensions of liquids. Although the ring method has been previously used to determine the surface tension of oils at high temperatures by Nellensteyn and Roodenburg, this method is highly influenced by the viscosity of the oil. Hence, it may give inaccurate results.

Since all asphalts are soluble in Benzene, and the surface tension of Benzene is easily measured with Du Nouy's ring, it is a simple matter to mix different weight proportions of Benzene and oil, thus determining the surface tension of these mixtures with the ring. Since all the solutions with percentages ranging from 45-99% Benzene are extremely liquid, one has no trouble measuring the surface tensions.

The procedure is very simple and routine. A small sample of the oil (3-5 grs) is weighed in an Erlmeyer flask or other bottle which has been weighed with a cork to fit. To the flask is added an approximate amount of Benzene which will comprise from 45-95% of the solution, the flask is corked and accurately weighed again to determine actual percent of Benzene. Three or more samples are weighed out and their Benzene percentage is spread evenly as possible between 45 and 95%. (Note. For percentages less than 45% Benzene the solutions are seldom sufficiently liquid, and slight difficulty may be encountered when cleaning the platinum ring, also an infinitesimally small error may occur due to the oil actually sticking to the ring, in addition for percentages above 95% Benzene, the surface tension varies very little from that of Benzene.)

With the accurate percentages of Benzene in each solution determined, the flasks are carefully rotated to guarantee a uniform mixture. Then a small watch glass, intensively cleaned and rinsed beforehand is filled and the surface tension of this sample is obtained with an accurately caliberated DuNouy Tensiometer. Since three or more samples are taken from each solution, the flasks are kept corked between trials. The operation of the Tensiometer is neither intricate nor complex, if used as per instructions given with the instrument. The ring is cleaned after each trial by heating red hot in a yellow flame. The mean Surface tension of the three trials is taken as the actual value of surface tension for each solution. These values are taken as ordinate values and plotted with the Benzene Percentage as abscissae, the curve will actually be a straight line. With the least error possible the curve will pass through the points of the surface tension of Benzene at a corresponding value of 100% Benzene. By extending the

curve through the point of 0 Percent Benzene, This if accurately scaled will be the value of the surface tension of the asphalt.

The results for oil Bare are shown - Table

| % Benzene | 100.0 | 88.7 | 79.5 | 72.6 | 50.3 | 0 |
|---|---|---|---|---|---|---|
| Surface Tension | 28.87 | 29.01 | 29.07 | 29.31 | 30.13 | 31.80 |

## Energy Relations

Asphalt through its property to act as a binder for aggregates has found its greatest field of application in road construction and improvement.

In an asphalt-aggregate system, the surface energies play an important part. These energies are given certain differentiating names and shall hereafter be called, Interfacial Energy, Energy of Immersion, Energy of Adhesion, Energy of Cohesion and Spreading Coefficient. Definitions of these terms are taken from Mack (1) and Anatole (4).

Interfacial Energy The energy at the interface of two coalescent substances. By Antonow's rule it is the difference between the surface tensions of the materials. R. Lemon (5) and N.P. Zwikker (5) show that this rule holds best for the solid-liquid interfaces.

Energy of Immersion When a solid is immersed in a liquid the surface disappears and in its place is found the same area of solid-liquid interface. The energy of immersion is equal to the surface tension of the immersed particle minus the energy of the interface.

SZ = Surface Tension of Aggregate

EI = Interfacial Energy

Energy of Immersion = SZ - EI (Mack)

Energy of Adhesion Whenever a solid coalesces with the surfaces of a liquid the surface energies disappear and the energy of the interface appear. The energies involved in this reaction is equal to the sum of the surface tension, minus the interfacial energy.

Energy of Adhesion = SZ + So - EI

The energy of Adhesion is the amount of energy per cm which must be applied at the interface in order to separate the substances.

Cohesion Energy is the internal energy between molecules of the same substance. This attraction energy is assumed to be twice the surface tension.

So = Surface Tension of Oil

Energy of Cohesion = 2 So.

The Spreading Coefficient. When a liquid spreads over a solid, attraction between the two phases occurs, the force of which is directed against the cohesion of the liquid, which is in a position of spreading. Thus the coefficient of spreading is equal to the energy of adhesion minus the energy of cohesion.

Coefficient of Spreading = SZ - SO - EI

By solving Mack's equations for adhesion tensions, the surface tensions of limestone is found to be approximately 71 dynes. Since this experiment is solely to compare the adhesive energies of the oils, and any assumed error is constant for all cases, the author believes that a const value of 70 dynes / cm is a suitable value for the surface tension of limestone. The following table shows the comparative calculated results.

| OIL | Surface Tension | Energy of Inteface | Energy of Immersion | Energy of Adhesion | Energy of Cohesion | Coefficient of Spreading |
|---|---|---|---|---|---|---|
| A | 37.2 | -32.8 | 102.8 | 140 | 74.4 | 65.6 |
| B | 31.8 | -38.2 | 108.2 | 140 | 63.6 | 76.4 |
| C | 31.9 | -38.1 | 108.1 | 140 | 63.8 | 76.2 |
| D | 31.9 | -38.1 | 108.1 | 140 | 63.8 | 76.2 |
| E | 33.2 | -36.8 | 106.8 | 140 | 66.4 | 73.6 |
| F | 31.6 | -38.4 | 108.4 | 140 | 63.2 | 76.8 |
| G | 35.3 | -34.7 | 104.7 | 140 | 70.6 | 69.4 |
| H | 33.8 | -36.2 | 106.2 | 140 | 67.6 | 72.4 |
| I | 32.1 | -37.9 | 107.9 | 140 | 64.2 | 75.8 |
| J | 32.9 | -37.1 | 107.1 | 140 | 63.8 | 74.2 |
| K | 32.3 | -37.7 | 107.7 | 140 | 64.6 | 75.4 |
| L | 32.8 | -37.2 | 107.2 | 140 | 65.6 | 74.4 |
| M | 32.5 | -37.5 | 107.5 | 140 | 65.0 | 75.0 |
| N | 32.3 | -37.7 | 107.7 | 140 | 64.6 | 75.4 |
| O | 33.6 | -36.4 | 106.4 | 140 | 67.2 | 72.8 |
| P | 31.8 | -38.2 | 108.2 | 140 | 63.6 | 76.4 |

Remarks: Since it is practically impossible for all the oils to have the same adhesion energy, it is obvious that at least one or both of previous assumptions; namely, the first assumption, Antonows Rule must hold for asphaltic oils and aggregates; second, that the surface tension for limestone can be assumed to have a constant value of 70 dymes: are false.

No general conclusions can be made from the data of the preceding paragraphs for the reasons previously stated. The author regrets that he cannot find any appreciable error in his computations; and, until further research is carried out along this line, he will be unable to state definitely which of his assumptions is incorrect.

## Binding Properties of Asphalts

The first attribute of an adhesive is that it should wet the solid on which it is placed. It should then change into a more or less tenacious solid. In road construction the asphalt-aggregate joint is

usually attacked by water before setting of the adhesive occurs. The first stages in the study of binders should be in the wetting properties. Since asphalts spread easily over most aggregates, wetting is comparatively simple and complete. But, nevertheless, the degree of wetting depends on (a) the nature of the liquid which will determine the specific wetting properties, (b) the viscosity of the liquid which will determine its rate of spreading, (c) the nature of the solid which will determine its tendency to be spread.

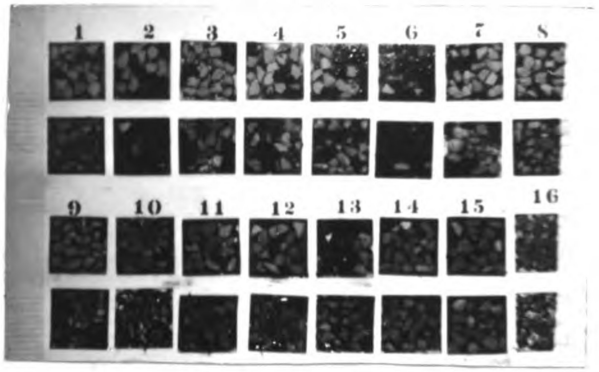
The second stage of study of binding properties is their condition after being water-soaked for some definite length of time.

A Glass Plate test is used to investigate the binding properties of asphalts after soaking. This test is accomplished by coating two pieces of glass plate (in this instance, three inches square) with oil films of uniform thickness. Granite and limestone, "½" size, which had been previously soaked for 24 hours and wiped dry with a clean coth, was placed on the two plates. One plate for each specific aggregate. Samples of sixteen different oils were spread on similar plates. After allowing the glass plates to remain in the open for fifteen minutes, they were placed in a container which had enough water to cover them to the depth of about three inches. This water was kept at room temperature ($20^{0}$C) throughout the test. These plates were allowed to soak for ten days, after which the glass plates were quickly inverted and held in this position to allow the stones whose bonds had been broken by the water to fall off. Through this test a comparative binding efficiency of the oils for granite and limestone is made. Also, under normal

conditions, this was also a test on the displacement of the oil from the plate glass surface. With each granite plate having almost the same film thickness as the corresponding limestone plate, the results were, as expected, very much alike.

Taken as a whole, the majority of the oils showed exceptionally good Bond for the limestone, with a few showing likewise for granite. The exceptionally poor oils were: F, approximately 2% efficient as a bond agent or, it was almost totally displaced from the stones by the water; oil M was an exception in the way it acted as suitable binder for the granite plate, but not for the limestone. This case was opposite to that of oil B, which showed good Bond for the limestone. Another characteristic of almost all of the plates was the condition of the oil film on the glass plate: with a few exceptions, the films were all broken and formed into weathered, disentegrated oil masses.

The exceptions spoken of in the previous paragraph were oils G, H, I, K, L, N, and O. They showed the least film weathering and practically no displacement of oils from either the stones or the glass plates. Taken as a comparative test, the plates showed the best oils for cold, dry stone patching.



The preceding snapshot shows, although none too clearly, the black plates--the ones whose oil bond was insufficient to hold the stones. Reading left to right, the top row beings with the limestone plate of oil A and so on to oil H. The plates in the second row are the corresponding granite plates of the oils. The third row begins with oil I on the left and ends with oil P on the right, with the corresponding granite plates below them. The following table compares the binding properties of each oil.

PLATE TEST - TEN-DAY SOAKING

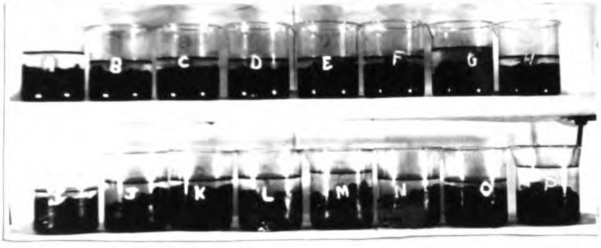
| Oils | Limestone Bond | Granite Bond | Film Weathered |
|---|---|---|---|
| A | Good | Good | Slightly |
| B | Poor | Very poor | Highly |
| C | Good | Good | Slightly |
| D | Very good | Good | Slightly |
| E | Fair | Fair | Highly |
| F | Exceptionally poor | Except. poor | Highly |
| G | Very good | Very good | Very slightly |
| H | Perfect | Perfect | Not weathered |
| I | Very good | Very good | No weathering |
| J | Good | Very good | No weathering |
| K | Poor | Very good | Slightly |
| L | Very good | Perfect | Slightly |
| M | Very poor | Very good | Slightly |
| N | Very good | Perfect | No weathering |
| O | Perfect | Perfect | No weathering |
| P | Very good | Fair | Highly |

Remarks: The various grades of bond for each oil is obtained by comparing the number of stones that remain on the plate after soaking, with the number originally placed on it before soaking. The weathered condition of the film denotes the degree of destruction of the film by the water.

In order to study more clearly the effects of displacing and weathering of the oils by water, a Boaker Test was devised to com-

plete the experiment. It consisted of samples of 150 gms of "$\frac{1}{2}$" limestone being coated with 1-1.5 gms of oil. In order to increase uniformity of films, these samples were warmed to 100$^{0}$C, allowed to cool for thirty minutes, then placed in numbered beakers and covered with distilled water. These beakers were set in a place well out of the sunlight and allowed to soak. They were inspected often enough to be sure that the stones were completely covered with water at all times.

After fifteen days of soaking, the beakers were inspected. With few exceptions, the oils had formed spherical drops on the stones. Oils B, G, and M, in addition, showed a slight change in color from black to slightly brown. Although the results were easily noted on sight, it was quite impossible to show distinct effects by snapshots.




On close scrutiny, the stones in beaker F appear much lighter then the others. This was caused by the almost complete displacement of the oil from the stones by the water. The following table shows the comparative results after a thirty-day period of soaking.

BEAKER TEST - THIRTY-DAY SOAKING

| Oils | Color | Condition of Film | Luster |
|---|---|---|---|
| A | Dark brown | Fair | Glossy |
| B | Light brown | Fair | Dull |
| C | Brown | Poor | Slight gloss |
| D | Black | Good | High gloss |
| E | Dark brown | Fair | Glossy |
| F | Dark brown | Very poor | Slight gloss |
| G | Light brown | Good | Dull |

BEAKER TEST - THIRTY-DAY SOAKING
(con't)

| | | | |
|---|---|---|---|
| H | Black | Very good | Glossy |
| I | Brown | Good | Dull |
| J | Brown | Very good | Dull |
| K | Black | Fair | High gloss |
| L | Black | Good | High gloss |
| M | Very light brown | Fair | Dull |
| N | Light brown | Very good | Dull |
| O | Black and brown | Very good | Partly glossy |
| P | Light brown | Fair | Dull |

Remarks: Only those oils whose color remained black were considered to be non-weathered. Also the films of these oils were in either very good, or at least fair, condition. The film conditions were graded as to the completeness of the present oil film on the stones. The oils having very poor or only fair conditions show oil displacement by water.

## Acid Test

In order to complete the analysis of the oils and to test the influence of acid on their properties, they were tested for their acid content.(7)

A small sample (5 gms) of the asphalt was boiled with a retort in 25 c.c. of benzene. Then 100 c.c. of slightly neutral alcohol was added to the retort and boiled for twenty minutes longer. The clear solution was decanted and 50 c.c. more alcohol was added to the residue, then boiled twenty minutes more under retort. This solution was decanted and the residue tested to make sure it was no longer acid. Then the total clear solution was mixed and 10 c.c. of barium chloride was added. After allowing it to cool, six drops of phenolphthalein were added to the solution as indicator, and it was titrated with .64% normal NAOH.

The Acid Equivalent was found to be equal to the Mgs NAOH necessary to neutralize 100 gms of oil.

Example: Oil B

Sample 5.0932 gms. - used .1 cc. .002593 gNAOH/cc

$$\frac{.1 \times .002593}{5.9032} \times 100 \times 1000 = 5.096 \text{ mg/100 gms oil}$$

TABLE I

Characteristics of Oils

| PROCESS | Steam Refined Residue | Cut Back Steam Residue And Gas Oil | | Blend of Steam Refined and Cracked Residue | | |
|---|---|---|---|---|---|---|
| OILS | J | F | C | L | B | E |
| Specific Gravity $25^0C/25^0C$ | .972 | .983 | .978 | 1.025 | .992 | .995 |
| Water & Sediment % | 0.0 | 0.0 | 0.4 | 0.0 | 0.3 | 0.0 |
| Flash Point-Cleveland Open Cup $^0C$ | 156 | 150 | 148 | 154 | 130 | 145 |
| Viscosity-Saybolt Furol $60^0C$ Sec. | 522 | 552 | 465 | 472 | 446 | 649 |
| Heterogeneity Test | Negative | Negative | Neg. | Positive | Sli. Pos. | Sli. Pos. |
| Distillation $^0C$ | | | | | | |
| $0^0 - 225^0$ o/o | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $0^0 - 315^0$ o/o | 0.0 | 0.5 | 0.2 | Trace | 1.5 | 0.0 |
| $0^0 - 360^0$ o/o | 1.5 | 3.0 | 7.0 | 1.0 | 7.0 | 0.5 |
| Test on Distillation Residue | | | | | | |
| Bitumen Soluble in $CCl_4$ o/o | 99.94 | 99.98 | 99.99 | 99.89 | 99.93 | 99.97 |
| Tests on 100 Penetration Residue | | | | | | |
| Actual Penetration of Residue | 95 | 107 | 93 | 100 | 105 | 93 |
| Heat Time for Residue Hrs. | 7 | 9½ | 6 | 3 | 11 | 11½ |
| Total Residue o/o | 79.7 | 82.3 | 78.8 | 80.1 | 79.1 | 80.1 |
| Ductility $25^0c$ 5cm/min. cmc. | 95 | 190 | 111 | 148 | 100 | 110 |
| " $4^0C$ "1 " | 7 | 9.5 | 6.5 | 7 | 5.5 | 6.5 |
| Asphaltenes % | 10. | 8.61 | 12.66 | 19.66 | 8.95 | 8.80 |
| Surface Tension Dynes/cm. | 32.85 | 31.56 | 31.88 | 32.67 | 31.81 | 33.26 |
| Plate Test -Limestone | Good | V.Poor | Good | V.Good | Poor | Fair |
| -Granite | V.Good | V.Poor | Good | Perfect | V.Poor | Fair |
| Beaker Test-Limestone | V.Good | V.Poor | Poor | Good | Fair | Fair |
| Acid Equivalent - MG/100 | 14.23 | 43.54 | 25.43 | 4.87 | 5.10 | 23.92 |

TABLE I - Continued

CHARACTERISTICS OF OILS

| Process | Steam and Vacuum Distillation | | | | | |
|---|---|---|---|---|---|---|
| Oil | D | G | I | K | M | P |
| Specific Gravity 25°/25°C | .989 | .984 | .990 | 1.009 | .996 | .976 |
| Water & Sediment % | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.00 |
| Flash Point Cleveland Open Cup °C | 214 | 140 | 140 | 180 | 194 | 208 |
| Viscosity-Saybolt Furol 60°C Sec. | 480 | 595 | 498 | 455 | 685 | 552 |
| Heterogeneity Test | Neg. | Neg. | Neg. | Neg. | Neg. | Neg. |
| Distillation °C | | | | | | |
| 0° - 225° % | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0° - 315° % | 0.0 | 5.0 | Trace | Trace | 0.0 | 0.0 |
| 0° - 360° % | 0.5 | 12.0 | 2.5 | 1.2 | Trace | 0.5 |
| Test on Distillation Residue | | | | | | |
| Bitumen Soluble in $CC/_4$ % | 99.94 | 99.91 | 99.95 | 99.98 | 99.98 | |
| Tests on 100 Penetration Residue | | | | | | |
| Actual Penetration of Residue | 90. | 107 | 99 | 96 | 98 | |
| Heat Time for Residue Hrs. | 22 | 5 | 9 | 4.75 | 6 | |
| Total Residue % | 75.5 | 75.5 | 76.2 | 77.4 | 76.3 | |
| Ductility 25°C 5cm 1 min. cms. | 142 | 125 | 106 | 150 | 94 | |
| " 4°C 5cm 1 min. cms. | 7.0 | 9.5 | 9.5 | 7.0 | 9.0 | |
| Asphaltenes % | 6.46 | 20.41 | 15.14 | 11.78 | 14.07 | 5.08 |
| Surface Tension Dynes/cm. | 31.92 | 35.26 | 32.11 | 32.35 | 32.45 | 31.75 |
| Plate Test - Limestone | V.Good | V.Good | V.Good | Poor | V.Poor | V.Good |
| - Granite | Good | V.Good | V.Good | V.Good | V.Good | Fair |
| Beaker Test - Limestone | Good | Good | Good | Fair | Fair | Fair |
| Acid Equivalent | 31.35 | 4.66 | 14.37 | 16.21 | 9.82 | 19.32 |

## TABLE I

## CHARACTERISTICS OF OILS

| Process | Blended Cracked Residues | | Straight Cracked | |
|---|---|---|---|---|
| Oils | N | H | A | O |
| Specific Gravity 25°c/25°C | .999 | 1.052 | 1.082 | 1.051 |
| Water and Sediment % | 0.00 | 0.02 | 0.00 | 0.40 |
| Flash Point Cleveland Open Cup °C | 170 | 155 | 152 | 210 |
| Viscosity Saybolt Furol 60°C, Sec. | 637 | 467 | 480 | 488 |
| Heterogeneity Test | Positive | Positive | Positive | Positive |
| Distillation | | | | |
| 0° to 225°C % | 0.0 | 0.0 | 0.0 | 0.0 |
| 0° to 315°C " | Trace | Trace | Trace | Trace |
| 0° to 360°C " | 0.5 | 5.5 | 1.8 | 0.5 |
| Test on distillation Residue | | | | |
| Bitumen Soluble in $CCl_4$% | 99.94 | 99.85 | 99.96 | 99.52 |
| Tests on 100 Penetration Residue | | | | |
| Actual Penetration of Residue | 91. | 94 | 96 | 107 |
| Heat Time for Residue Hrs. | 4.5 | 2.5 | 1.5 | 7 |
| Total Residue % | 81.2 | 81.8 | 84.0 | 84.6 |
| Ductility 25°C 5cm 1 min.Cms. | 150 | 135 | 105 | 70 |
| " 4°C " 1 " | 5.5 | 1.0 | 0.0 | 4.5 |
| Asphaltenes - Percent | 13.04 | 19.05 | 26.00 | 15.29 |
| Surface Tension - Dynes/cm. | 32.30 | 33.77 | 37.19 | 35.55 |
| Plate Test Limestone | V. Good | Perfect | Good | Perfect |
| Granite | Perfect | Perfect | Good | Perfect |
| Beaker Test - Limestone | V. Good | V. Good | Fair | V. Good |
| Acid Equivalent | 10.55 | 4.91 | 9.41 | 26.92 |

## SUMMARY AND CONCLUSION

1. The DuNouys Ring and Percent Benzene method, if accepted, is the most practical yet proposed for determining surface tensions.

2. Antonows Rule, although valid for pure liquids, does not hold for asphalts and aggregates.

3. The Plate Test is a simple, but effective, test for the bonding properties of asphalts.

4. The Beaker Test is by far the most efficient of the tests on oil displacement by water.

5. The oils having the highest surface tension were either cracks or blends of cracks. The only exception to this conclusion is oil G, which is a steam refined crude.

6. Oils having low surface tensions were found to have fairly poor bonding qualities. However, this is not true for oil D.

7. Oil F is an exceptional example, having the lowest surface tension. It is also outstanding as the poorest binder of the oils.

8. Compared according to their asphaltene content, the oils with the highest surface tension also have the greater asphaltene content.

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