# An Evaluation of Aging of Recycled Asphalt

Final Report

Project 83-3

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## ABSTRACT

Old bituminous concrete is being recycled into new surfaces. If a reasonable life is to be attained, the old asphalt must be softened. This paper compares the rate of hardening of old binder mixed with several materials as softening agents. Heat and hot air were used to simulate aging. Aged asphalt mixed with a soft asphalt aged at the rate of a new AC-20. The two recycling agents tested aged significantly faster than a new AC-20.

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# AN EVALUATION OF AGING OF RECYCLED ASPHALT

## INTRODUCTION

In recent years there has been increased interest in recycling old bituminous pavement. As the price of binder materials increases, the savings that can be realized by reusing the asphalt present in the pavement may be significant.

Recycling can take several forms. Probably the simplest is that of breaking up the old surface, blading to shape as a base and covering with a new surface. In one such process, the pavement is processed by a traveling hammermill. The top six or eight inches of the existing surface and base is processed into a uniform material which is then leveled and compacted as a base. Where needed, new aggregate can be added to correct grading deficiencies. A new plant mix wearing course is then placed. The major benefit from this procedure is the elimination of the discontinuities which existed where cracks were present in the old pavement. Obviously reflection cracks can not occur if no cracks exist in the base when the new surface is placed. Mixing the old surfacing with the old base should provide better base material as base fines are stabilized by the binder from the old base.

The maximum potential savings from use of the old asphalt is not realized when the old pavement is recycled into a base, as the binding character of the asphalt is not fully utilized. Milling off part of the pavement with the millings then used as part of the new pavement represents a higher use of the binder. Aging has hardened the asphalt through selective evaporation of the lighter portions of the asphalt and combination of some molecules into larger molecules. If the pavement was recycled by simply heating and relaying, in a very short period of time the surfacing would be harder than before treatment. This would be the result of oxidation during heating and placing. New cracking would occur at that time and the life cycle cost of the treatment would be high. To obtain a reasonable life, the large molecules must be broken up or smaller molecules must be reintroduced during processing. If the recycling is to be considered successful, the life of the pavement must be sufficiently long to make the life cycle costs equal to or less than that of a totally new pavement. Some form of laboratory test, which predicts aging character, must be applied if life cycle costs are to be estimated.

Several years ago D. A. Anderson carried out a Masters Thesis study with the Civil Engineering Department of the University of Connecticut. This project compared the age hardening of an 85/100 pen asphalt binder produced as the end product of petroleum distillation and of an equivalent binder made as a blend of 40/50 pen and 120/150 pen binders. The procedure used was the measurement of viscosity after progressively longer periods of aging through exposure to heat and air. The blend hardened sharply faster than the straight run material. Figure 1 is a copy of the hardening graph from that study and Figure 2 is the molecular size distribution typically hypothesied for such materials. Work done by C. E. Dougan in a later study that followed the change in molecular distribution again used thin film aging and demonstrated that molecules grow larger with aging time. Figure 3 taken from that paper is an example of this growth.

Asphalt ring molecules must increase by finite increments. That is, molecule A in Figure 4 can not grow into the shapes shown at B but must increase by a complete ring as in C. In Dougan`s studies, the increase is size was small. That is, small molecules combined with larger molecules, but large ones did not combine with other large molecules. This implies that a surplus of small molecules such as in the blend of Figure 2 supplies the small units to be linked to the middle sized molecules for increased size. The straight run

85-100 had less small molecules so aged slower. This implies that the light ends of a gap graded molecular distribution evaporate or cross link more readily than the light ends from a continuous molecular size distribution. AC graded materials would behave much like the penetration graded materials of Figure 2.

The blending of an aged asphalt with a soft recycling agent would result in an exaggeration of the conditions created by blending two asphalts. As the aged asphalt is harder than a 40/50 pen asphalt and the recycling agent more volatile than an 120/150 pen asphalt, the resulting material would have a greater molecular gap than the blended asphalt referred to above and the rate of hardening would be even faster. This set of conditions indicates that the life of a recycled pavement could be shorter than that of a new pavement. If the costs are comparable, economics might well indicate that a better solution would be to dispose of the old pavement in some other way and use a new mix for the replacement pavement.

TEST PROCEDURE

A simple test procedure based on that used in the former study was used to predict comparative recycled pavement life. The sliding plate viscosity was determined for a new AC-20. Using the rolling thin film oven described in ASTM method 02872, a sample of the AC-20 was aged for one, two and three hours at 325F and the viscosity measured for each. As the viscosity of the three hour aged AC-20 had increased to 3 or 4 times the original, this material was used as typical of that in the aged pavement. As a simulated recycling operation, various recycling agents were mixed with the aged AC-20 material in proportions that returned the viscosity to that of the original AC-20. The blended materials were then alternately aged at 325F and viscosity tested at 70F for one, two, and three hours in a manner similar to the original testing of the new AC-20. Test results are presented in Figure 5.

The new AC-20 aged at a nearly uniform rate for the period of three hours. Both the Mobilsol and the Cyclogen at two and three hours aged sharply faster than the new AC-20. As a comparison, enough AC-2.5 was added to some of the aged AC-20 to give the original viscosity and aging again carried out. This mix aged only slightly faster than the new material. That the two aged at nearly identical rates was to be expected as the current production of AC-20 is by blending a hard and a soft asphalt cement. Thus the material recycled by using AC-2.5 may have been very similar to the new AC-20. All four samples were similar at one hour. Although correlations of hours of aging to years of pavement life are not available, it is clear that both of the recycling agents gave mixes with the potential of early aging. This could make recycling of the pavement of questionable economic benefit. At three hours the viscosities rank inversely proportional to the percent of light material added to get the original viscosity. That is, more AC 2.5 was required and the resulting material hardened in the oven slower than either the Mobilsol or the Cyclogen blends. The Mobilsol required the least and hardened the most.

## CONCLUSIONS

As measured by thin film laboratory aging, aged AC-20 binder rejuvenated by either Mobilsol or Cyclogen ages faster than that treated with AC-2.5. This has serious implications for the durability of recycled binders. The use of the high temperatures required for accelerated aging may have caused damage to the binder greater than from natural aging. Until long term monitoring of recycled pavement can be carried out and a definitive answer found to the question of comparative life, a soft asphalt should be used for recycling.

REFERENCES

David A. Anderson, Artificial Aging of Various Penetration Grade Asphalts, Masters Thesis, 1964, University of Connecticut.

Charles E. Dougan, Molecular Size Distributions of Asphalt as Determined by Gel Permeation Chromatography, Ph.D. Thesis, 1970, University of Connecticut.

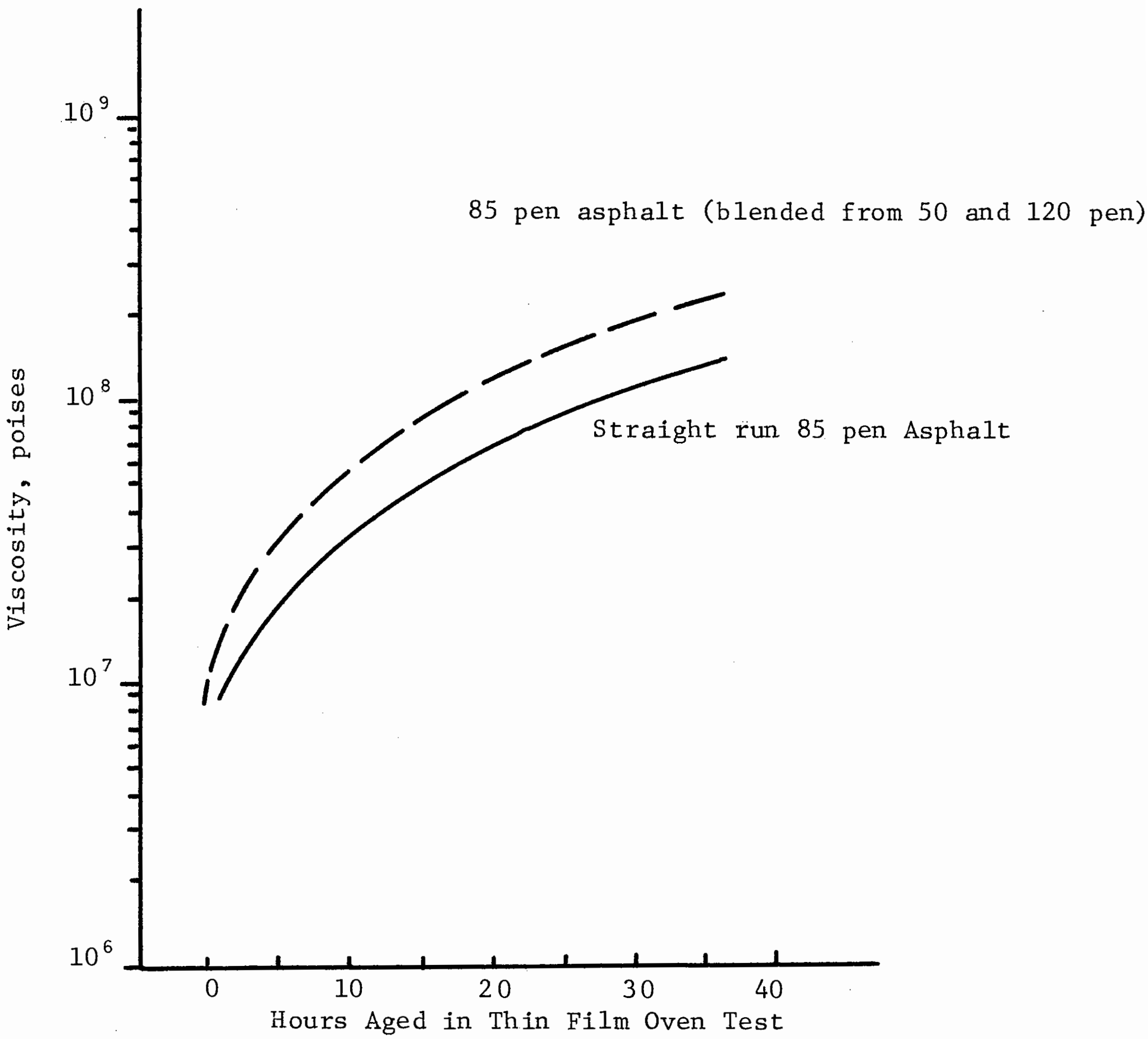


FIGURE 1, Asphalt Hardening with Age from Anderson [1]

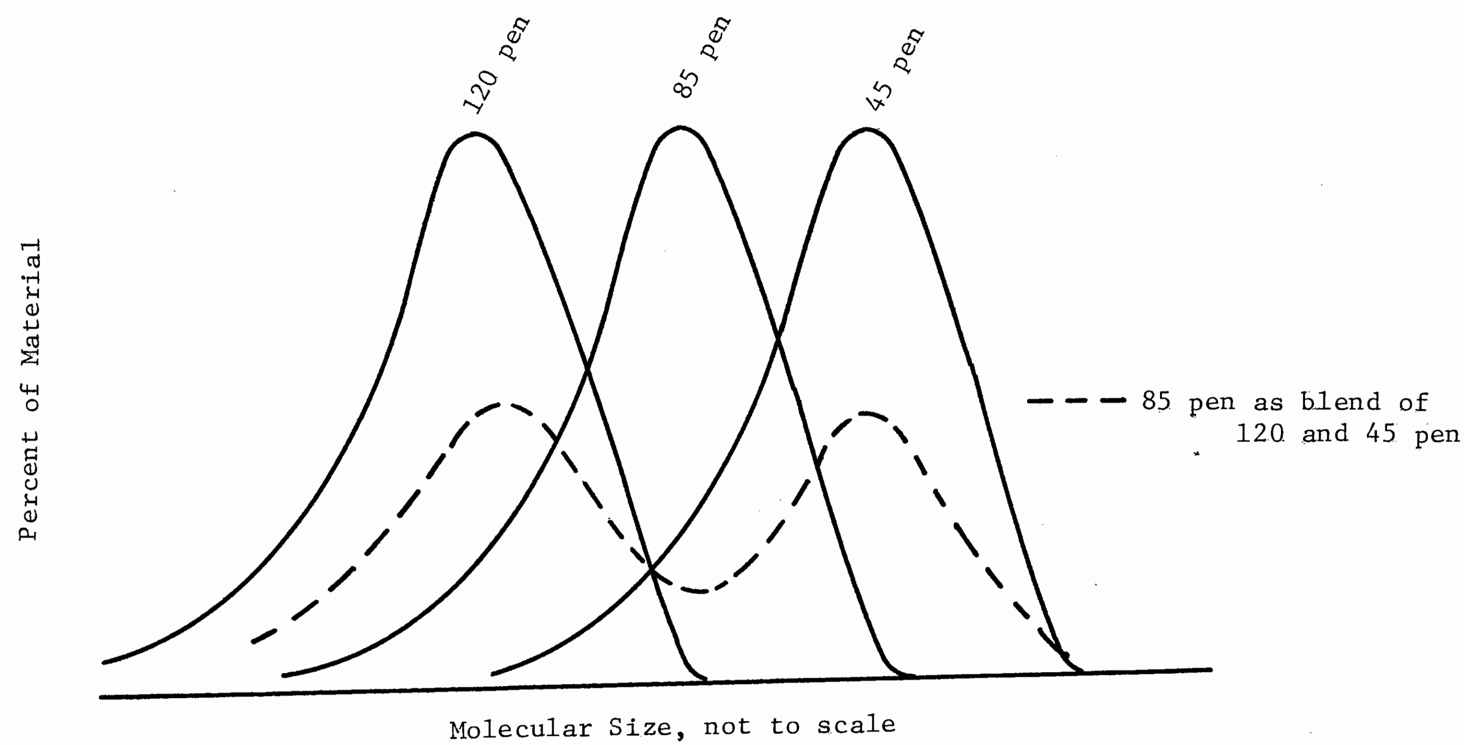


FIGURE 2, Representation of Molecular Size Distribution for Asphalts

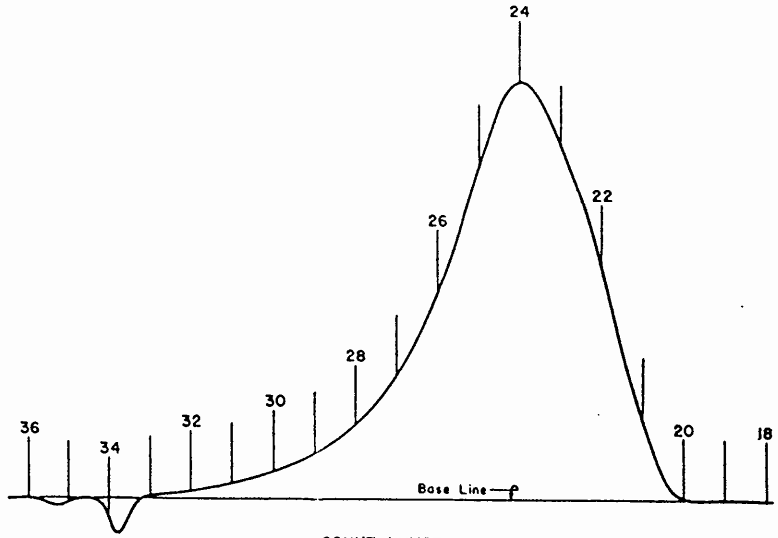


FIGURE 7

GEL PERMEATION CHROMATOGRAM-UNAGED ASPHALT

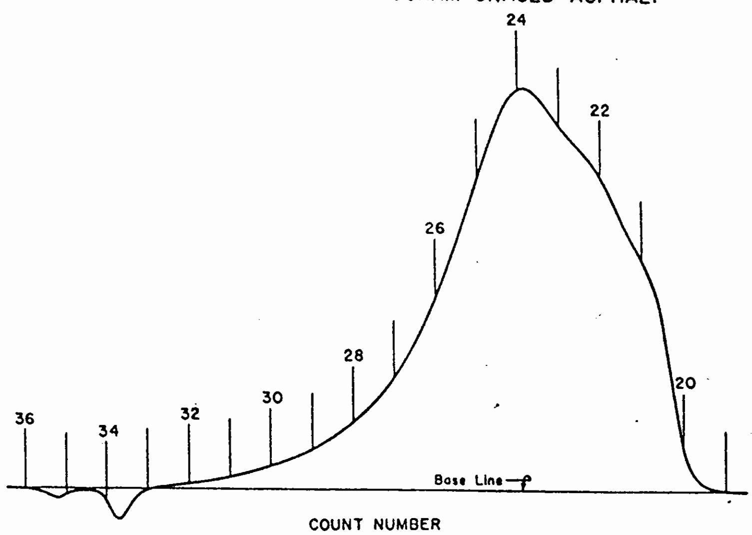


FIGURE 9

GEL PERMEATION CHROMATOGRAM-ASPHALT AGED 5-HOURS

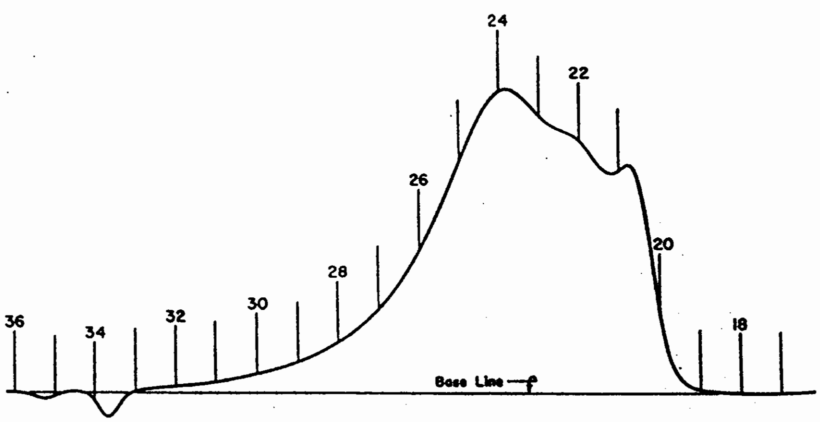


FIGURE 10

GEL PERMEATION CHROMATOGRAM-ASPHALT AGED 10-HOURS

Figure 3, Molecular Size Distribution from Dougan[2]

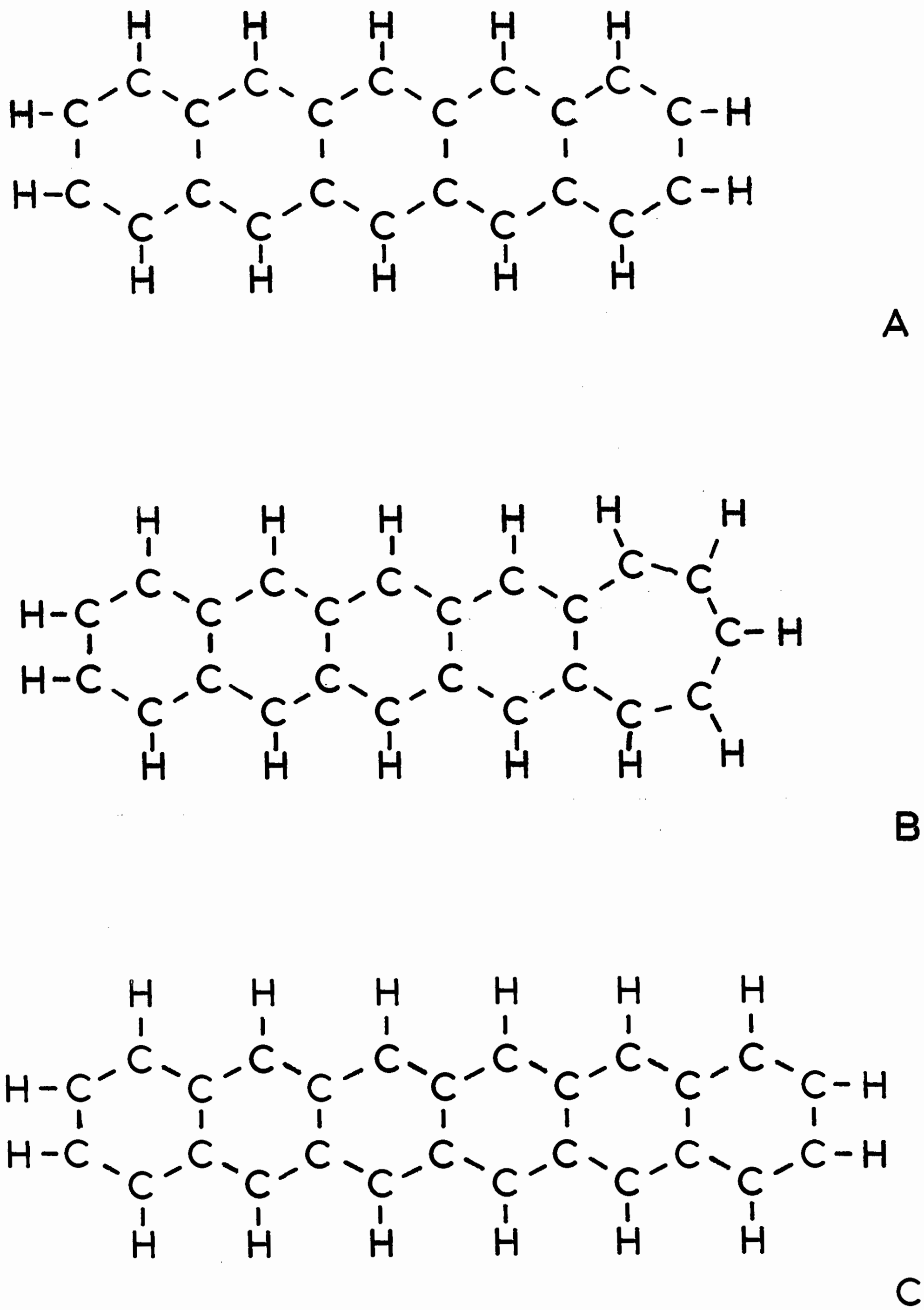


FIGURE 4, Simple Hydrocarbon Molecules

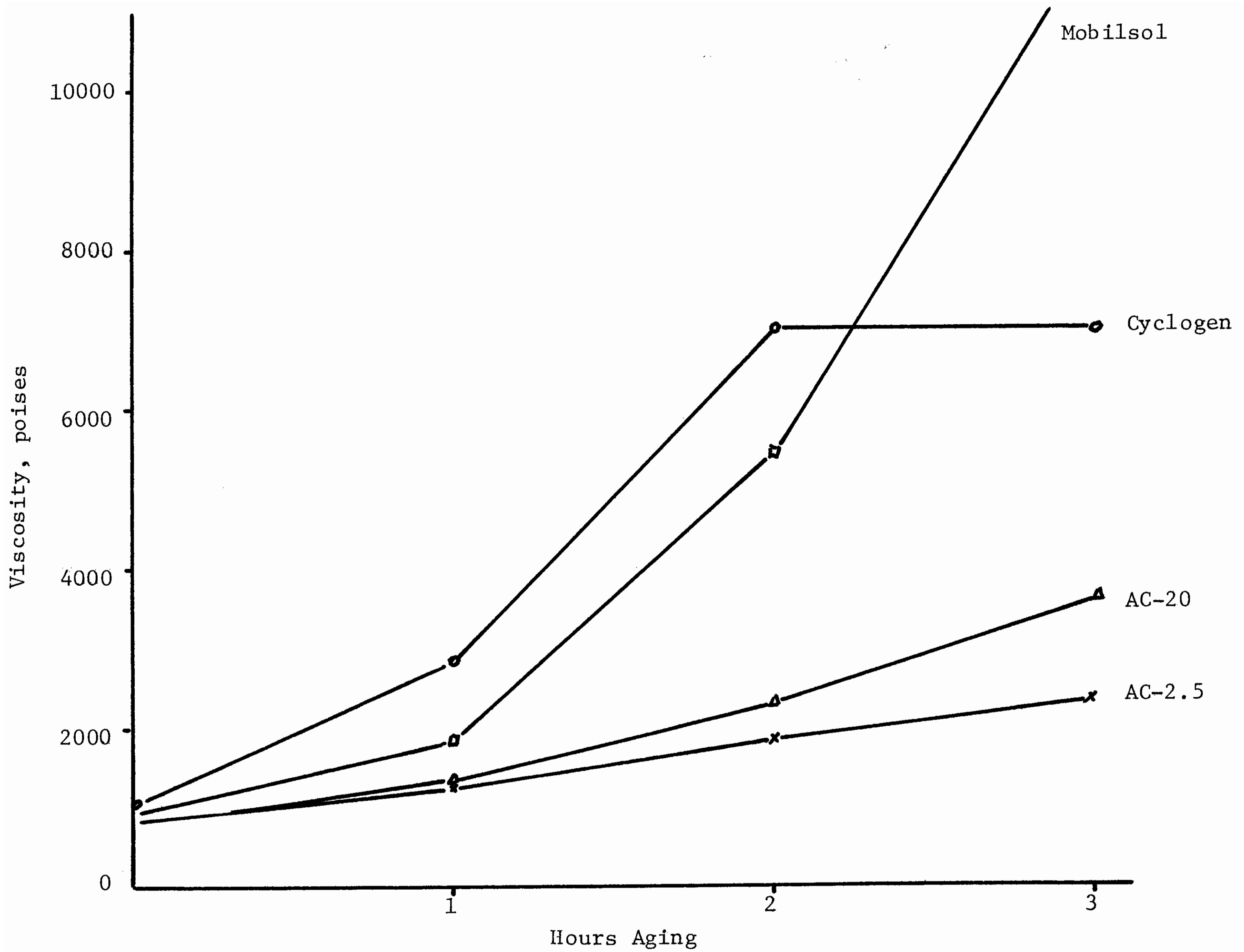


FIGURE 5, Viscosity versus Aging, Shear Rate 0.1 $sec^{-1}$

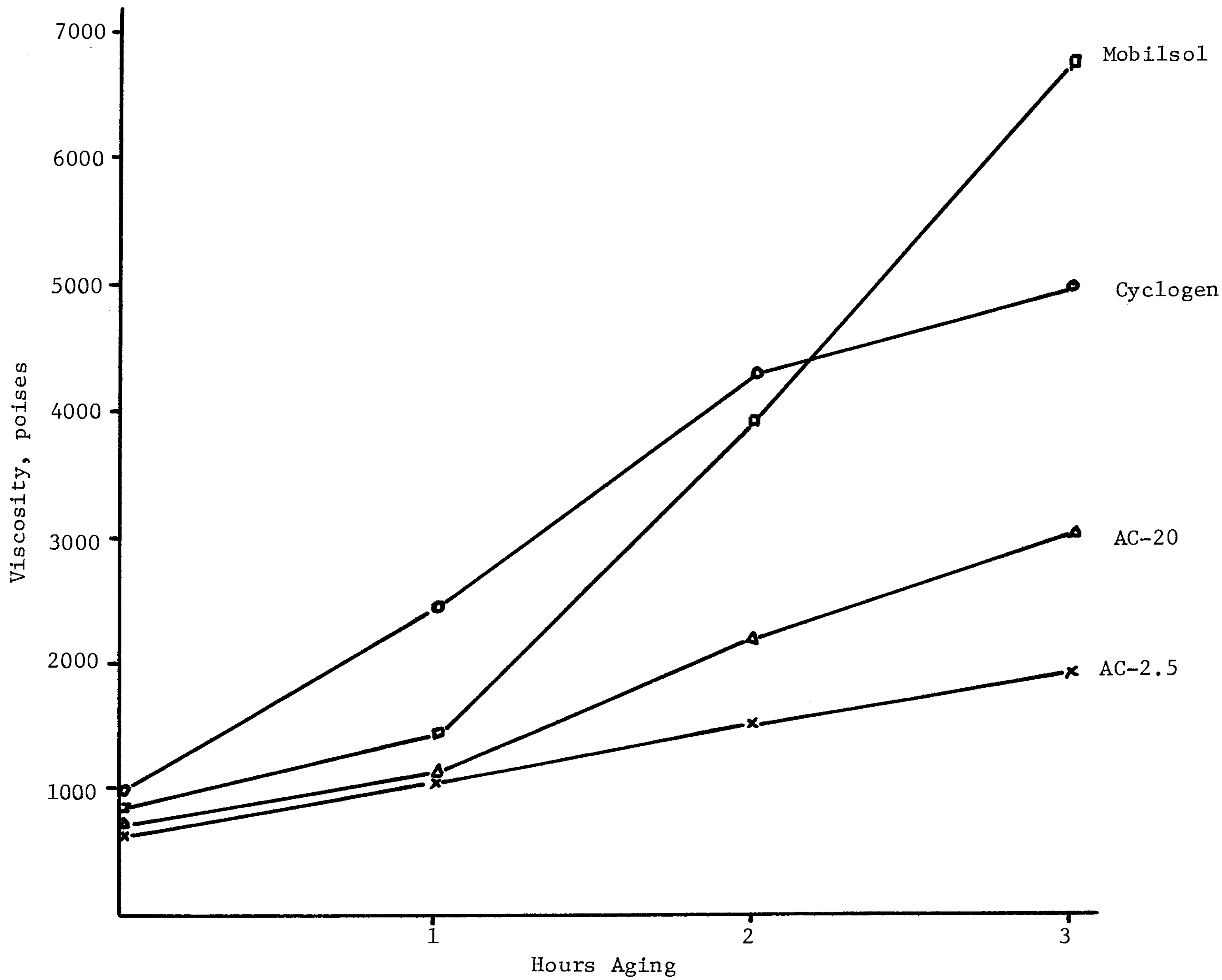


FIGURE 6, Viscosity versus Aging, Shear Rate 0.2 $sec^{-1}$

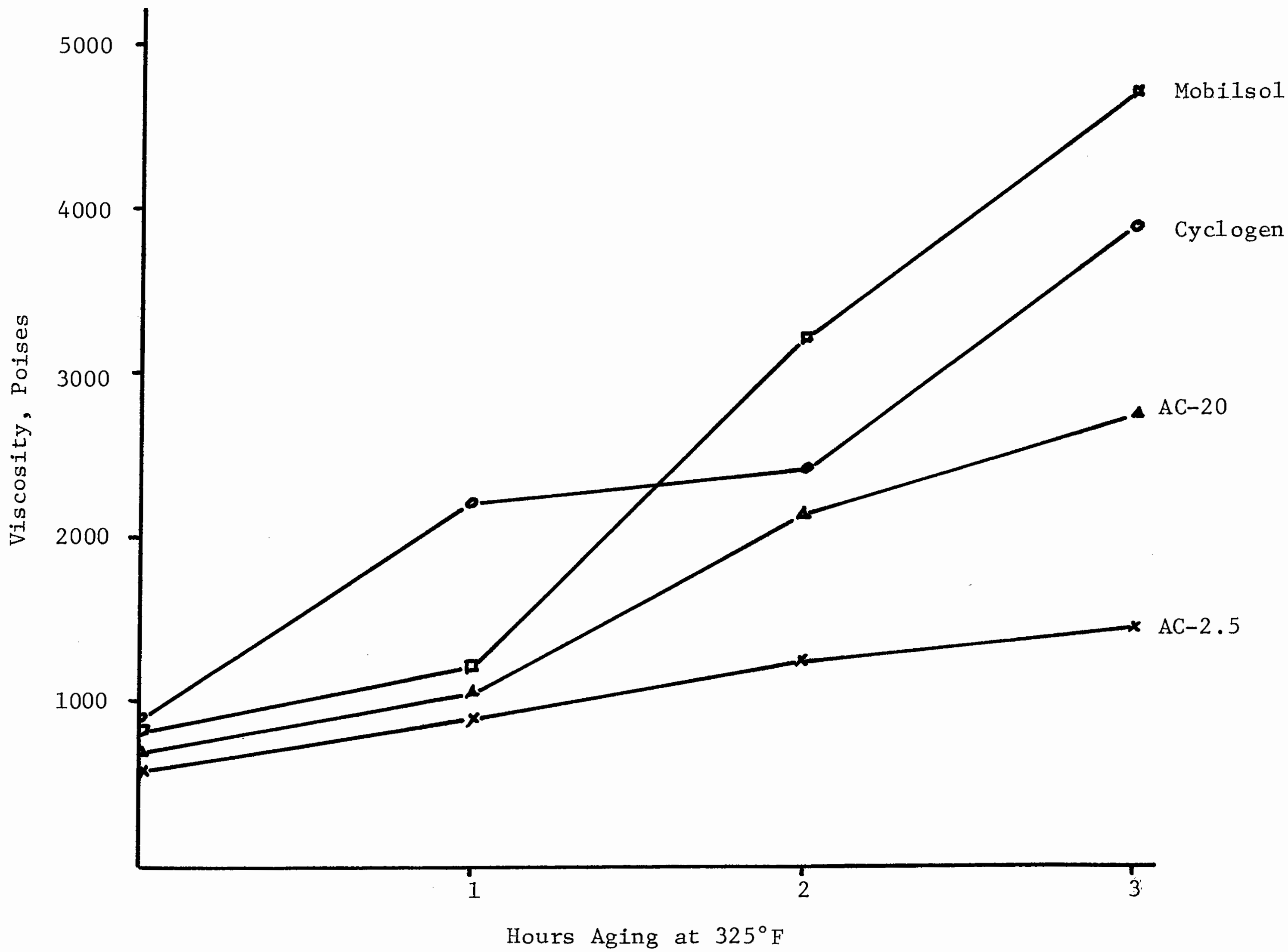


FIGURE 7, Viscosity versus Aging, Shear Rate 0.3 $sec^{-1}$

# APPENDIX I

## TESTING DETAILS

The viscosity tests were carried out using a Hallikanian Sliding Plate Viscosimeter. All tests were at 40C and on 20 by 30 millimeter glass plates. The thickness of a pair of plates was determined at each corner with a micrometer. After heating the plates to 170F, a drop of asphalt was placed between and the plates squeezed together until the thickness of the layer was .007 inches or less and uniform.

Aging was carried out by one hour increments in the rolling thin film oven at 325F. AC-20, aged three hours, was used as the aged asphalt to be recycled. Trial blends were made with each recycling agent until the viscosity of the blend was the same as that of the unaged AC-20. Each blend was then aged by hourly increments with the viscosity checked at each interval.

As the film thicknesses were different and the viscosity was unknown, shear rate could not be controlled. Multiple samples of each material were tested giving a range of shear rates. The data was processed as:

Shear Rate(1/sec) = velocity(mm/sec/film thickness(mm)

Shear Stress(g/cm2) = 98.1 x Force(gram)/area of plates(cm2)

Viscosity(poises) = Shear Stress/Shear Rate

In order to compare the viscosity regardless of the change in area during shearing, the shear stress was multiplied by a correction of factor of (30 - displacement)/30.

For each material and aging period the viscosity was plotted versus the shear rate Figures I-1 to I-4. From these curves, the viscosity at 0.1, 0.2, and 0.3 per second shear rates were read and plotted as Figure 5.

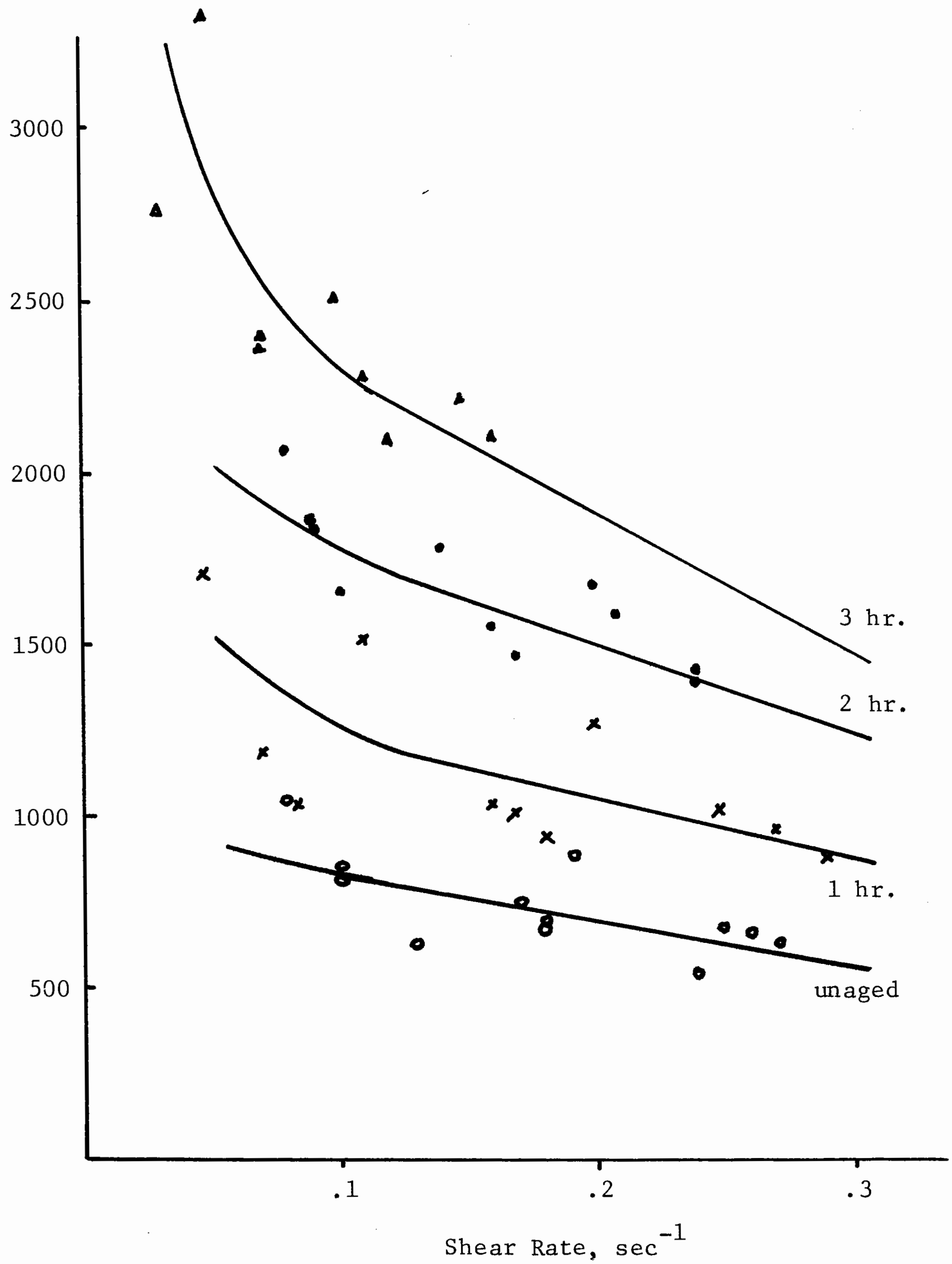


FIGURE I-1, Viscosity versus Shear Rate,
60% Aged 3 Hour AC-20 + 40% Unaged AC-25

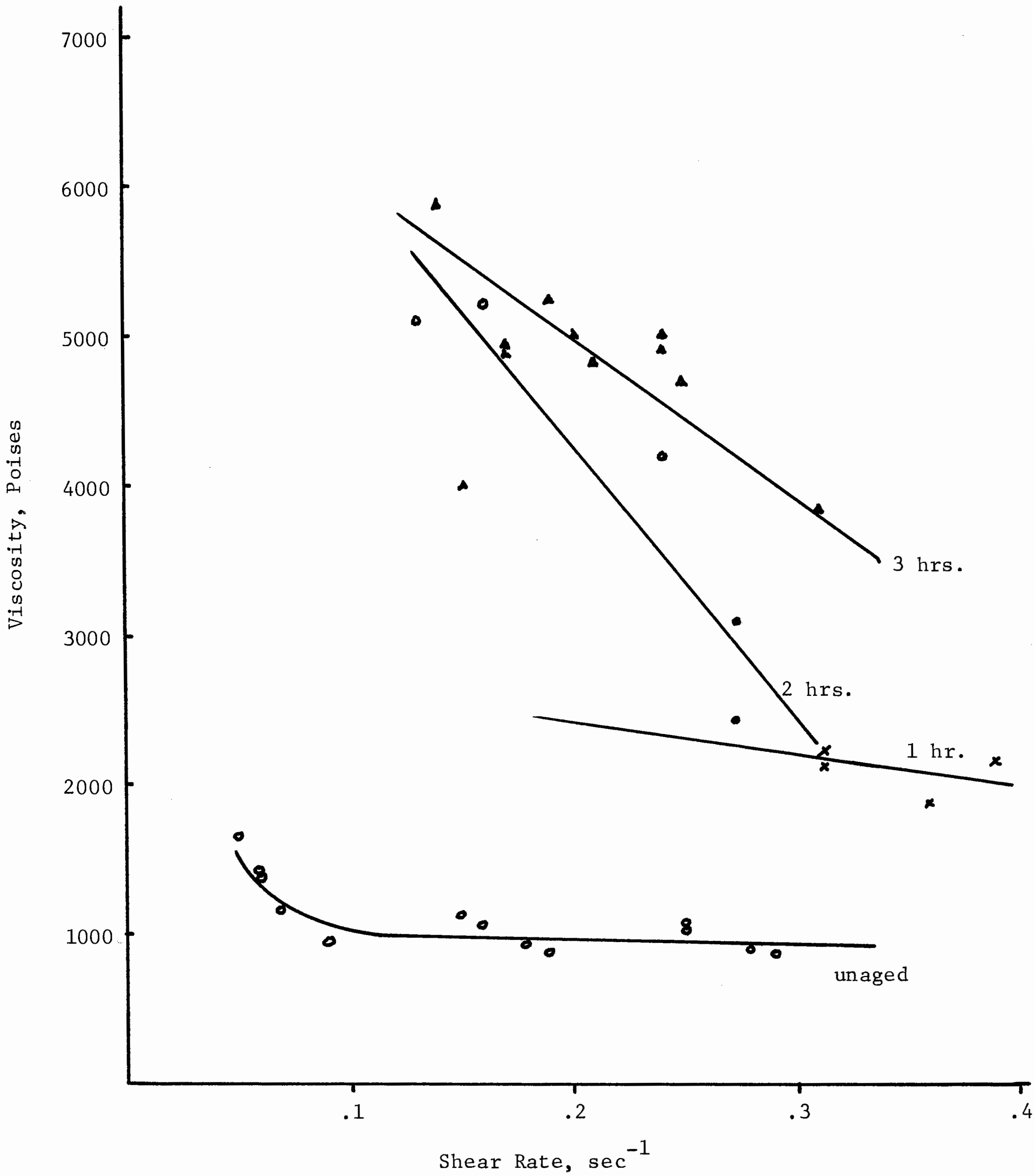


FIGURE I-2, Viscosity versus Shear Rate,
85% Aged 3 Hour AC-20 + 15% Cyclogen

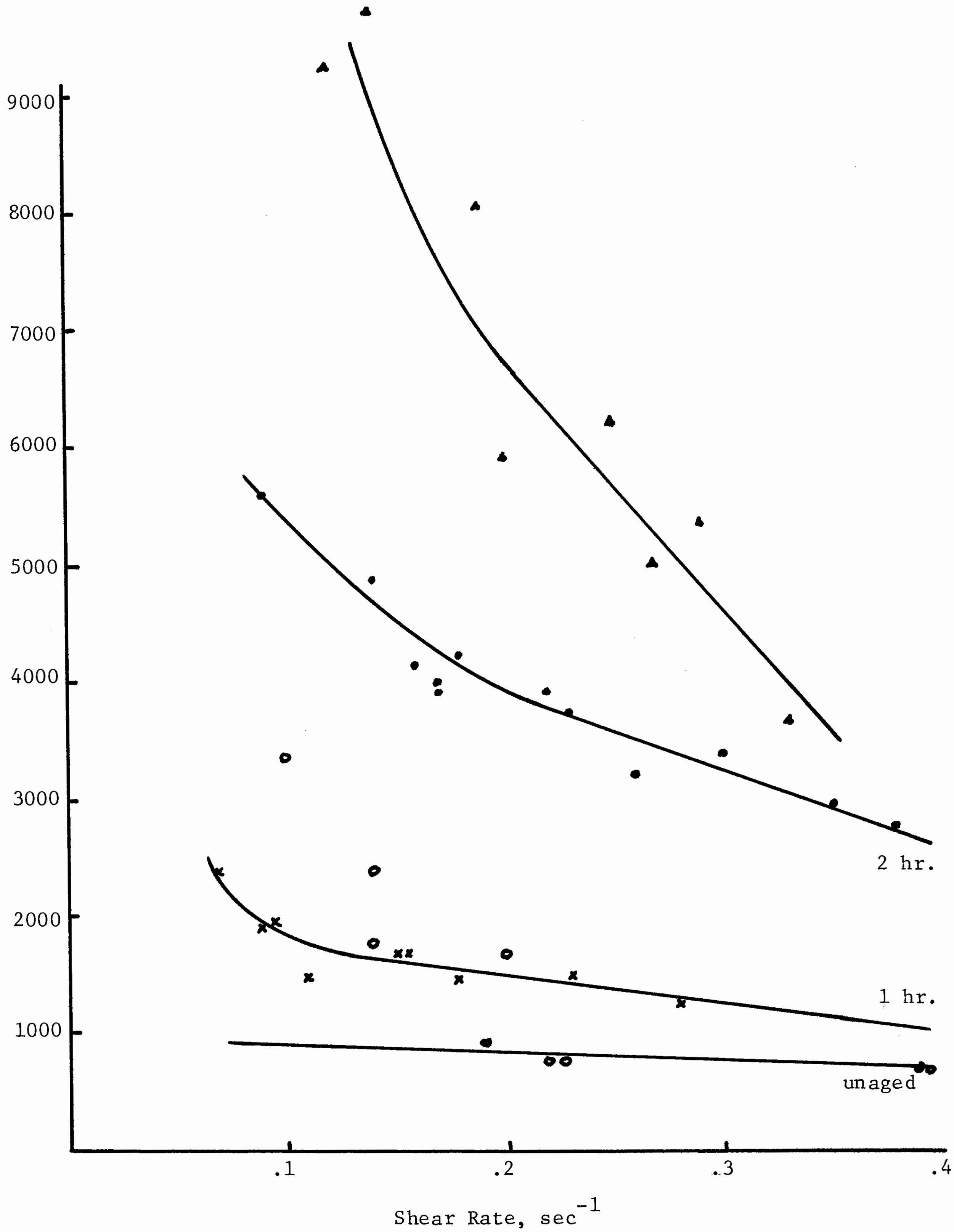


FIGURE I-3, Viscosity versus Shear Rate,
82% Aged 3 Hour AC-20 + 18° Mobilsol 120

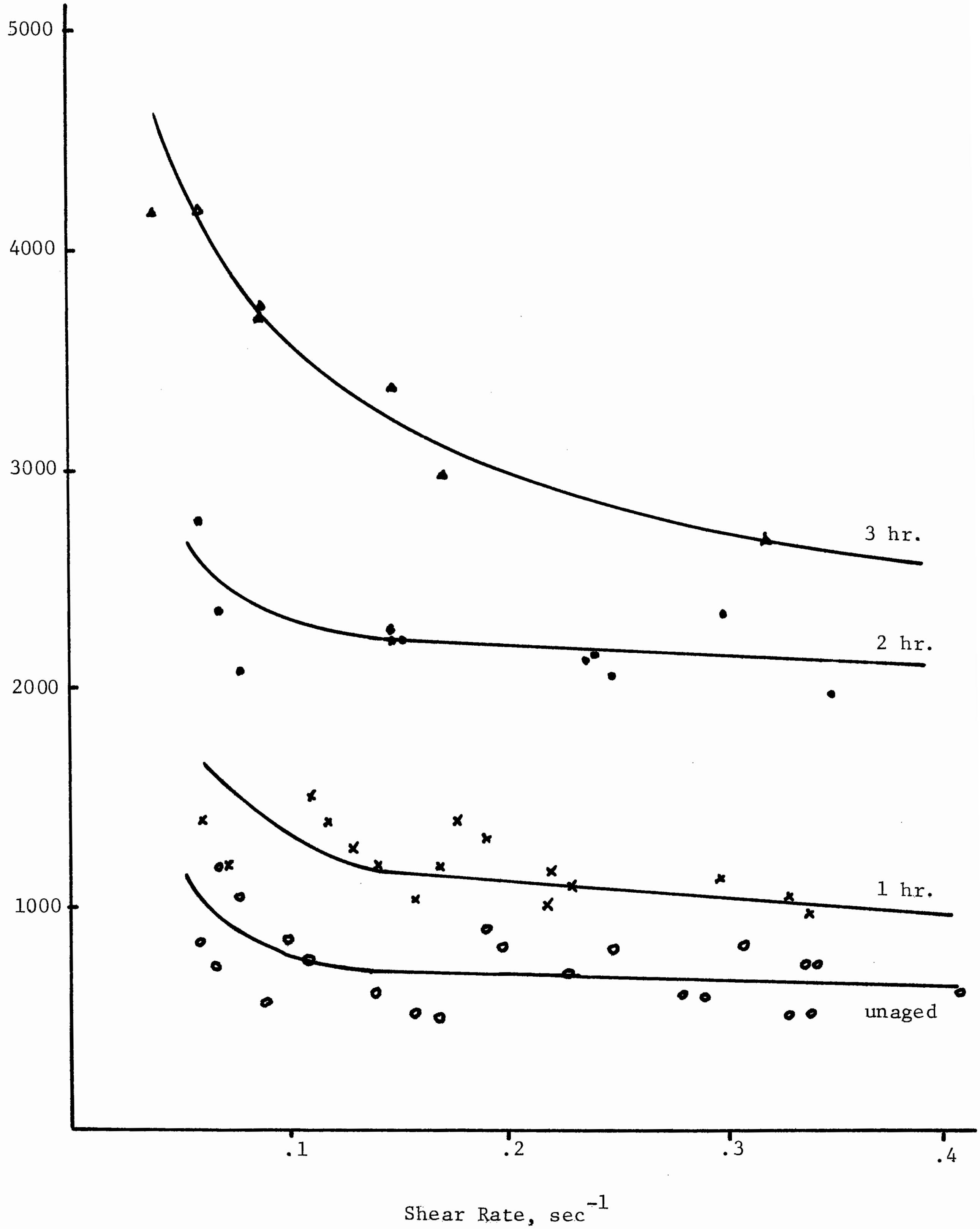


FIGURE I-4, Viscosity versus Shear Rate, 100% AC-20

# APPENDIX II

| THICKNESS MILLIMETER | LOAD GRAM | VELOCITY MM/SEC | DISPLACEMENT MILLIMETER | SHEAR RATE 1/SEC | VISCOSITY POISES |
|---|---|---|---|---|---|
| 90% AGED 3 HOURS AC-20 + 10% MOBILSOL BLEND UNAGED | | | | | |
| .01778 | 100 | .0035 | .27 | .19 | 876.26 |
| .01778 | 150 | .0085 | .60 | .47 | 537.34 |
| .01778 | 200 | .0135 | .70 | .75 | 450.50 |
| .00508 | 100 | .0030 | .20 | .59 | 281.52 |
| .00508 | 150 | .0070 | .63 | 1.37 | 184.52 |
| .00508 | 200 | .0095 | .90 | 1.87 | 181.92 |
| .01524 | 100 | .0035 | .17 | .22 | 754.27 |
| .01524 | 200 | .0120 | .50 | .78 | 430.24 |
| .02032 | 100 | .0045 | .13 | .22 | 753.22 |
| .02032 | 150 | .0080 | .30 | .39 | 641.02 |
| .02032 | 200 | .0150 | .45 | .73 | 458.93 |
| 82% AGED 3 HOUR AC-20 + 18% MOBILSOL 120 BLEND AGED 1 HOUR | | | | | |
| .05080 | 100 | .0040 | .15 | .07 | 2368.85 |
| .05080 | 150 | .0075 | .45 | .14 | 1794.71 |
| .05080 | 200 | .0120 | .58 | .23 | 1463.04 |
| .05588 | 100 | .0065 | .33 | .11 | 1516.63 |
| .05588 | 150 | .0105 | .65 | .18 | 1405.44 |
| .05588 | 200 | .0160 | .85 | .28 | 1212.92 |
| .04064 | 100 | .0040 | .20 | .09 | 1845.55 |
| .04064 | 150 | .0065 | .50 | .15 | 1677.93 |
| .04064 | 200 | .0095 | .80 | .23 | 1474.08 |
| .05080 | 100 | .0050 | .20 | .09 | 1845.55 |
| .05080 | 150 | .0080 | .45 | .15 | 1675.06 |
| .05080 | 200 | .0105 | .60 | .20 | 1683.65 |
| 82% AGED 3 HOUR AC-20 + 18% MOBILSOL 120 BLEND AGED 2 HOUR | | | | | |
| .03556 | 200 | .0050 | .15 | .14 | 2368.92 |
| .03556 | 400 | .0050 | .40 | .16 | 4180.68 |
| .03556 | 500 | .0080 | .60 | .22 | 3826.50 |
| .03556 | 600 | .0110 | .85 | .30 | 3396.20 |
| .04064 | 400 | .0073 | .50 | .17 | 3948.11 |
| .04064 | 500 | .0097 | 1.00 | .23 | 3710.60 |
| .04064 | 600 | .0157 | 1.72 | .38 | 2763.71 |
| .07620 | 400 | .0133 | .15 | .17 | 3901.82 |
| .07620 | 500 | .0200 | .40 | .26 | 3215.92 |
| .07620 | 600 | .0270 | .85 | .35 | 2911.02 |
| .07620 | 200 | .0770 | .20 | .10 | 3322.10 |
| .07620 | 300 | .0070 | .35 | .09 | 5564.88 |
| .07620 | 400 | .0110 | .60 | .14 | 4810.42 |
| .07620 | 500 | .0140 | .80 | .18 | 4700.88 |
| 82% AGED 3 HOUR AC-20 + 18% MOBILSOL 120 BLEND AGED 3 HOUR | | | | | |
| .05588 | 700 | .0050 | .40 | .08 | 14632.50 |
| .05588 | 800 | .0120 | .95 | .21 | 6491.23 |
| .05588 | 900 | .0140 | 1.25 | .25 | 6198.24 |
| .04572 | 700 | .0095 | .37 | .20 | 5847.10 |

APPENDIX II

| THICKNESS MILLIMETER | LOAD GRAM | VELOCITY MM/SEC | DISPLACEMENT MILLIMETER | SHEAR RATE 1/SEC | VISCOSITY POISES |
|---|---|---|---|---|---|
| 82% AGED 3 HOUR AC-20 + 18% MOBILSOL 120 BLEND AGED 3 HOUR | | | | | |
| .04572 | 800 | .0125 | .80 | .27 | 5022.81 |
| .04572 | 900 | .0135 | 1.20 | .29 | 5334.03 |
| .06096 | 700 | .0075 | .45 | .12 | 9771.50 |
| .06096 | 800 | .0090 | .75 | .14 | 9670.28 |
| .06096 | 900 | .0120 | .90 | .19 | 8057.47 |
| .02540 | 700 | .0085 | .16 | .33 | 3518.75 |
| .02540 | 800 | .0120 | .75 | .47 | 2880.51 |
| .02540 | 900 | .0160 | 1.00 | .62 | 2477.74 |
| 90% AGED 3 HOUR AC-20 + 10% CYCLOGEN BLEND UNAGED | | | | | |
| .11684 | 100 | .0125 | .28 | .10 | 1665.50 |
| .11684 | 200 | .0260 | .84 | .22 | 1543.18 |
| .11684 | 150 | .0180 | 1.26 | .15 | 1722.33 |
| .07620 | 100 | .0088 | .20 | .11 | 1510.00 |
| .07620 | 150 | .0155 | .55 | .20 | 1260.60 |
| .07620 | 200 | .0220 | .81 | .28 | 1211.25 |
| .07620 | 100 | .0090 | .19 | .11 | 1509.54 |
| .07620 | 150 | .0150 | .35 | .19 | 1318.00 |
| .07620 | 200 | .0225 | .85 | .29 | 1171.10 |
| .12700 | 100 | .0135 | .17 | .10 | 1659.40 |
| .12700 | 150 | .0200 | .54 | .15 | 1680.20 |
| .12700 | 200 | .0300 | .67 | .23 | 1467.52 |
| 85% AGED 3 HOUR AC-20 + 15% CYCLOGEN BLEND UNAGED | | | | | |
| .08636 | 50 | .0060 | .14 | .06 | 1381.33 |
| .08636 | 100 | .0140 | .59 | .16 | 1051.93 |
| .08636 | 150 | .0245 | 1.07 | .28 | 919.60 |
| .06604 | 50 | .0050 | .25 | .07 | 1188.42 |
| .06604 | 100 | .0130 | .60 | .19 | 886.10 |
| .06604 | 150 | .0170 | .91 | .25 | 1020.96 |
| .05842 | 50 | .0035 | .19 | .05 | 1660.40 |
| .05842 | 100 | .0090 | .29 | .15 | 1110.73 |
| .05842 | 150 | .0175 | .55 | .29 | 869.37 |
| .08636 | 50 | .0082 | .18 | .09 | 922.11 |
| .08636 | 100 | .0157 | .48 | .18 | 931.55 |
| .08636 | 50 | .0058 | .73 | .06 | 1409.16 |
| .08636 | 150 | .0220 | 1.44 | .25 | 1039.88 |
| 85% AGED 3 HOUR AC-20 + 15% CYCLOGEN BLEND AGED 1 HOUR | | | | | |
| .03048 | 400 | .0110 | .50 | .36 | 1864.38 |
| .03048 | 500 | .0150 | .90 | .49 | 1735.73 |
| .03048 | 600 | .0205 | 1.90 | .67 | 1577.50 |
| .00762 | 400 | .0040 | .50 | .52 | 1290.73 |
| .00762 | 500 | .0060 | .95 | .78 | 1092.26 |
| .00762 | 600 | .0100 | 1.20 | 1.31 | 787.21 |
| .01270 | 400 | .0040 | .14 | .31 | 2138.99 |
| .01270 | 500 | .0060 | .30 | .47 | 1773.04 |
| .01270 | 600 | .0830 | .45 | 6.53 | 153.91 |

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|---|---|---|---|---|---|
| 85% AGED 3 HOUR AC-20 + 15% CYCLOGEN BLEND AGED 1 HOUR | | | | | |
| .01270 | 400 | .0040 | .35 | .31 | 2154.16 |
| .01270 | 500 | .0050 | .50 | .39 | 2151.23 |
| .01270 | 600 | .0080 | .65 | .62 | 1632.12 |
| .04572 | 500 | .0200 | .25 | .43 | 1934.72 |
| .04572 | 600 | .0285 | .57 | .62 | 1627.69 |
| .04572 | 400 | .0145 | .95 | .31 | 2198.64 |
| .03302 | 400 | .0090 | .25 | .27 | 2464.96 |
| .03302 | 500 | .0090 | .50 | .27 | 3107.33 |
| .03302 | 600 | .0140 | .75 | .42 | 2417.57 |
| .06858 | 400 | .0090 | .35 | .13 | 5136.84 |
| .06858 | 500 | .0115 | .60 | .16 | 5261.43 |
| .06858 | 600 | .0170 | .80 | .24 | 4238.00 |
| .04572 | 400 | .0145 | .45 | .31 | 2161.45 |
| .04572 | 500 | .0185 | .70 | .40 | 2111.75 |
| .04572 | 600 | .0240 | 1.25 | .52 | 1986.61 |
| 85% AGED 3 HOUR AC-20 + 15% CYCLOGEN BLEND AGED 3 HOUR | | | | | |
| .04826 | 500 | .0070 | .23 | .14 | 5938.35 |
| .04826 | 600 | .0100 | .43 | .20 | 5021.95 |
| .04826 | 700 | .0120 | .77 | .24 | 4939.25 |
| .06096 | 500 | .0103 | .28 | .16 | 5204.81 |
| .06096 | 600 | .0120 | .45 | .19 | 5289.84 |
| .06096 | 700 | .0158 | .58 | .25 | 4711.08 |
| .05080 | 500 | .0090 | .03 | .17 | 4901.94 |
| .05080 | 600 | .0130 | .60 | .25 | 4040.80 |
| .05050 | 700 | .0160 | .90 | .31 | 3841.03 |
| .08128 | 500 | .0145 | .75 | .17 | 4977.35 |
| .08128 | 600 | .0175 | .97 | .21 | 4871.76 |
| 60% AGED 3 HOUR AC-20 + 40% UNAGED AC-2.5 BLEND UNAGED | | | | | |
| .10160 | 50 | .0180 | .60 | .10 | 829.10 |
| .10160 | 75 | .0180 | .60 | .17 | 742.76 |
| .10160 | 100 | .0265 | 1.15 | .26 | 659.88 |
| .10668 | 50 | .0090 | .20 | .08 | 1038.12 |
| .10668 | 75 | .0195 | .33 | .18 | 695.11 |
| .10668 | 100 | .0210 | .70 | .19 | 889.15 |
| .07620 | 50 | .0105 | .25 | .13 | 639.92 |
| .07620 | 75 | .0183 | .55 | .24 | 525.25 |
| .07620 | 100 | .0195 | .95 | .25 | 681.56 |
| .08382 | 50 | .0090 | .10 | .10 | 827.70 |
| .08382 | 75 | .0155 | .30 | .18 | 694.44 |
| .08382 | 100 | .0230 | .55 | .27 | 622.51 |

# APPENDIX II

| THICKNESS MILLIMETER | LOAD GRAM | VELOCITY MM/SEC | DISPLACEMENT MILLIMETER | SHEAR RATE 1/SEC | VISCOSITY POISES |
|---|---|---|---|---|---|
| 60% AGED 3 HOUR AC-20 + 40% UNAGED AC-2.5 BLEND AGED 1 HOUR | | | | | |
| .08636 | 50 | .0070 | .10 | .08 | 1034.62 |
| .08636 | 100 | .0145 | .30 | .16 | 1041.62 |
| .08636 | 150 | .0255 | .60 | .29 | 870.86 |
| .05588 | 50 | .0050 | .10 | .08 | 1034.62 |
| .05588 | 100 | .0095 | 1.10 | .17 | 1007.52 |
| .05588 | 150 | .0155 | 1.55 | .27 | 966.59 |
| .05842 | 50 | .0042 | .10 | .07 | 1182.42 |
| .05842 | 100 | .0110 | .55 | .18 | 933.77 |
| .05842 | 150 | .0150 | .75 | .25 | 1015.36 |
| .09398 | 100 | .0110 | .40 | .11 | 1520.18 |
| .09398 | 150 | .0195 | .75 | .20 | 1269.20 |
| .09398 | 50 | .0055 | .95 | .05 | 17023.80 |
| 60% AGED 3 HOUR AC-20 + 40% UNAGED AC-2.5 BLEND AGED 2 HOUR | | | | | |
| .09144 | 100 | .0080 | .15 | .08 | 2072.75 |
| .09144 | 150 | .0154 | .25 | .16 | 1559.81 |
| .09144 | 200 | .0195 | .50 | .21 | 1598.04 |
| .06604 | 100 | .0070 | .08 | .10 | 1654.40 |
| .06604 | 150 | .0115 | .30 | .17 | 1470.58 |
| .06604 | 200 | .0160 | .50 | .24 | 1398.29 |
| .07112 | 100 | .0065 | .25 | .09 | 1848.66 |
| .07112 | 150 | .0105 | .55 | .14 | 1800.85 |
| .07112 | 200 | .0175 | .85 | .24 | 1415.08 |
| .10414 | 100 | .0095 | .12 | .09 | 1840.66 |
| .10414 | 150 | .0150 | .48 | .14 | 1796.57 |
| .10414 | 200 | .0210 | .75 | .20 | 1692.30 |
| 60% AGED 3 HOUR AC-20 + 40% UNAGED AC-2.5 BLEND AGED 3 HOUR | | | | | |
| .13208 | 200 | .0210 | .25 | .15 | 2218.46 |
| .13208 | 100 | .0098 | .45 | .07 | 2393.00 |
| .13208 | 150 | .0188 | .75 | .14 | 1813.14 |
| .16510 | 100 | .0120 | .08 | .07 | 2363.42 |
| .16510 | 150 | .0185 | .30 | .11 | 2272.72 |
| .16510 | 200 | .0265 | .60 | .16 | 2104.56 |
| .19304 | 50 | .0075 | .05 | .03 | 2754.33 |
| .19304 | 50 | .0075 | .05 | .03 | 2754.33 |
| .19304 | 100 | .0186 | .35 | .09 | 1854.88 |
| .10304 | 150 | .0245 | .60 | .12 | 2104.58 |
| .17880 | 50 | .0045 | .10 | .02 | 4138.50 |
| .17780 | 100 | .0100 | .25 | .05 | 3327.60 |

# APPENDIX II

| THICKNESS MILLIMETER | LOAD GRAM | VELOCITY MM/SEC | DISPLACEMENT MILLIMETER | SHEAR RATE 1/SEC | VISCOSITY POISES |
|---|---|---|---|---|---|
| 100% AC-2.5 UNAGED | | | | | |
| .04318 | 10 | .0025 | .04 | .05 | 330.40 |
| .04318 | 20 | .0090 | .15 | .20 | 165.80 |
| .04318 | 30 | .0155 | .72 | .35 | 144.88 |
| .05080 | 10 | .0040 | .09 | .07 | 236.28 |
| .05080 | 20 | .0103 | .48 | .20 | 167.65 |
| .05080 | 30 | .0200 | .70 | .39 | 129.94 |
| .01524 | 50 | .0010 | .05 | .06 | 1377.16 |
| .01524 | 100 | .0027 | .23 | .17 | 978.05 |
| .01524 | 200 | .0063 | .35 | .41 | 814.36 |
| .01524 | 400 | .0130 | .65 | .85 | 793.65 |
| .01524 | 600 | .0183 | .90 | 1.20 | 850.50 |
| .01524 | 1100 | .0370 | 1.25 | 2.42 | 782.60 |
| .01778 | 50 | .0035 | .12 | .19 | 435.94 |
| .01778 | 100 | .0048 | .30 | .26 | 641.00 |
| .01778 | 200 | .0065 | .43 | .36 | 929.97 |
| .01778 | 400 | .0155 | .60 | .87 | 774.09 |
| .01778 | 600 | .0230 | .80 | 1.29 | 788.46 |
| .01778 | 1100 | .0425 | 1.20 | 2.39 | 791.05 |
| .01778 | 50 | .0025 | .13 | .14 | 591.78 |
| .01778 | 100 | .0035 | .20 | .19 | 874.21 |
| .01778 | 200 | .0065 | .27 | .36 | 924.97 |
| .01778 | 400 | .0140 | .40 | .78 | 857.57 |
| .01778 | 600 | .0230 | .60 | 1.29 | 783.10 |
| .01778 | 1100 | .0400 | .80 | 2.24 | 832.46 |
| .01778 | 50 | .0020 | .15 | .11 | 753.72 |
| .01778 | 100 | .0035 | .20 | .19 | 874.21 |
| 100% AC-2.5 UNAGED | | | | | |
| .01778 | 200 | .0080 | .30 | .44 | 757.56 |
| .01778 | 400 | .0170 | .40 | .95 | 704.11 |
| .01778 | 600 | .0230 | .60 | 1.29 | 783.10 |
| .01778 | 1100 | .0420 | .90 | 2.36 | 792.85 |
| .02032 | 50 | .0025 | .15 | .12 | 690.91 |
| .02032 | 100 | .0035 | .30 | .17 | 980.35 |
| .02032 | 200 | .0070 | .45 | .34 | 985.35 |
| .02032 | 400 | .0160 | .58 | .78 | 862.83 |
| .02032 | 600 | .0220 | .72 | 1.08 | 939.20 |
| .02032 | 1100 | .0390 | .88 | 1.91 | 978.97 |
| 50% AGED 3 HOUR AC-20 + 50% UNAGED AC-2.5 BLEND UNAGED | | | | | |
| .05334 | 50 | .0125 | .10 | .23 | 359.86 |
| .05334 | 100 | .0300 | .65 | .56 | 301.16 |
| .05334 | 75 | .0300 | 1.29 | .56 | 230.91 |
| .04572 | 45 | .0105 | .08 | .22 | 338.36 |
| .04572 | 50 | .0120 | .22 | .26 | 319.61 |
| .04572 | 75 | .0210 | .76 | .04 | 317.40 |
| .04572 | 100 | .0275 | .99 | .60 | 284.38 |

# APPENDIX II

| THICKNESS MILLIMETER | LOAD GRAM | VELOCITY MM/SEC | DISPLACEMENT MILLIMETER | SHEAR RATE 1/SEC | VISCOSITY POISES |
|---|---|---|---|---|---|
| 0% AGED 3 HOUR AC-20 + 50% UNAGED AC-2.5 BLEND UNAGED | | | | | |
| .08636 | 50 | .0080 | .07 | .09 | 918.77 |
| .08636 | 75 | .0115 | .23 | .13 | 959.23 |
| .08636 | 100 | .0175 | .56 | .20 | 840.65 |
| .11684 | 50 | .0180 | .19 | .15 | 553.46 |
| .11684 | 75 | .0295 | .48 | .25 | 503.04 |
| .11684 | 100 | .0390 | .98 | .33 | 516.87 |
| 100% AC-20 AGED 2 HOURS | | | | | |
| .08890 | 100 | .0063 | .13 | .07 | 2367.28 |
| .08890 | 200 | .0140 | .38 | .15 | 2228.19 |
| .08890 | 300 | .0230 | 1.40 | .25 | 2076.92 |
| .08890 | 400 | .0290 | 1.80 | .32 | 2194.12 |
| .12700 | 100 | .0110 | .20 | .08 | 2076.25 |
| .12700 | 200 | .0195 | .40 | .17 | 2229.66 |
| .12700 | 300 | .0315 | 1.05 | .24 | 2137.29 |
| .12700 | 400 | .0450 | 1.55 | .35 | 1988.42 |
| .12192 | 100 | .0080 | .35 | .06 | 2782.33 |
| .12192 | 200 | .0185 | .85 | .15 | 2264.13 |
| .12192 | 300 | .0300 | 1.30 | .24 | 2155.91 |
| .12192 | 400 | .0375 | 1.60 | .30 | 2323.93 |
| 100% AC-20 AGED 3 HOURS | | | | | |
| .14986 | 200 | .0135 | .25 | .09 | 3697.44 |
| .14986 | 100 | .0068 | .45 | .04 | 4187.75 |
| .14986 | 300 | .0230 | .75 | .15 | 3384.60 |
| .18288 | 200 | .0120 | .10 | .06 | 5518.33 |
| .18288 | 100 | .0053 | .35 | .02 | 8347.00 |
| .18288 | 300 | .0160 | .50 | .08 | 6292.25 |
| .06096 | 100 | .0045 | .20 | .07 | 2372.85 |
| .06096 | 150 | .0040 | .40 | .06 | 4180.66 |
| .06096 | 200 | .0060 | .50 | .09 | 3728.77 |
| .06096 | 300 | .0105 | .70 | .17 | 2981.29 |
| 100% AC-20 UNAGED | | | | | |
| .05588 | 50 | .0100 | .10 | .17 | 486.88 |
| .05588 | 100 | .0185 | .55 | .33 | 509.33 |
| .05588 | 150 | .0200 | .85 | .53 | 480.58 |
| .10160 | 50 | .0085 | .25 | .02 | 1039.87 |
| .10160 | 100 | .0210 | .45 | .20 | 837.55 |
| .10160 | 100 | .0350 | 1.45 | .34 | 509.94 |
| .05080 | 50 | .0052 | .30 | .10 | 833.30 |
| .05080 | 100 | .0100 | .70 | .19 | 889.15 |
| .05080 | 150 | .0160 | 1.05 | .31 | 827.32 |
| .07874 | 50 | .0060 | .10 | .07 | 1182.42 |
| .07874 | 100 | .0165 | .45 | .20 | 837.55 |
| .07874 | 150 | .0270 | .95 | .34 | 751.73 |
| .03048 | 30 | .0030 | .03 | .09 | 550.44 |

# APPENDIX II

| THICKNESS MILLIMETER | LOAD GRAM | VELOCITY MM/SEC | DISPLACEMENT MILLIMETER | SHEAR RATE 1/SEC | VISCOSITY POISES |
|---|---|---|---|---|---|
| 100% AC-20 UNAGED | | | | | |
| .03048 | 50 | .0045 | .10 | .14 | 591.21 |
| .03048 | 100 | .0090 | .22 | .29 | 573.13 |
| .03048 | 150 | .0130 | .47 | .42 | 598.64 |
| .03048 | 200 | .0200 | .76 | .65 | 520.87 |
| .04318 | 30 | .0030 | .05 | .06 | 826.33 |
| .04318 | 50 | .0070 | .19 | .16 | 518.87 |
| .04318 | 100 | .0100 | .29 | .23 | 724.39 |
| .04318 | 150 | .0180 | .56 | .41 | 615.12 |
| .04318 | 200 | .0235 | .83 | .54 | 628.48 |
| .04064 | 30 | .0030 | .35 | .07 | 715.42 |
| .04064 | 50 | .0045 | .42 | .11 | 760.63 |
| .04064 | 100 | .0115 | .51 | .28 | 599.46 |
| .04064 | 150 | .0142 | .85 | .34 | 749.41 |
| 100% AC-20 AGED 1 HOUR | | | | | |
| .07112 | 50 | .0050 | .25 | .07 | 1188.42 |
| .07112 | 100 | .0105 | .40 | .14 | 1194.42 |
| .07112 | 150 | .0170 | .85 | .23 | 1107.43 |
| .07112 | 200 | .0235 | 1.30 | .33 | 1045.27 |
| .06096 | 100 | .0070 | .19 | .11 | 1509.00 |
| .06096 | 150 | .0140 | .40 | .22 | 1140.18 |
| .09398 | 100 | .0115 | .40 | .12 | 1393.50 |
| .09398 | 150 | .0170 | .60 | .18 | 1403.05 |
| .08636 | 100 | ,9120 | .15 | .13 | 1275.53 |
| .08636 | 150 | .0165 | .50 | .19 | 1324.68 |
| .10922 | 100 | .0180 | .15 | .16 | 1036.37 |
| .10922 | 200 | .0380 | .70 | .34 | 993.76 |
| .10922 | 300 | .0630 | 1.20 | .57 | 904.59 |
| .12192 | 50 | .0080 | .22 | .06 | 1385.00 |
| .12192 | 100 | .0175 | .44 | .14 | 1196.07 |
| .12192 | 150 | .0270 | .92 | .22 | 1160.59 |
| .12192 | 200 | .0375 | 1.27 | .30 | 1148.59 |

# APPENDIX III

## APPLICATION OF TEST METHOD TO RECYCLING

The test procedure used can be expanded to provide a means for making recycling decisions. Figure 5 clearly indicates that the use of the heaviest material possible as the recycling agent will give the best resistance to aging. The quantities used are dependent on plant equipment. The single most important factor is how the reclaimed material is to be heated. Passing the material through the standard dryer would burn up a large portion of the binder. Most plants in the State of Connecticut were not planned for heating of asphalt-aggregate mixtures. Until such a time as the recycling of plant mixes becomes widespread, the most expedient procedure to solve the heating problem is to overheat the new aggregate. Adding the overheated new aggregate to the recycled material in the pugmill will raise the entire batch to the desired temperature. The temperature of the mix would depend upon the temperatures and proportions of the materials used. The degree to which the dryer can heat the aggregate then determines the proportions which can be used. Heat balance dictates that:

$$(100-N)\ (Tm-To)\ \ Ho + \%as \times N(Tm-Tas) \times Has/100 = N(Tag-Tm) \times Hag$$

$$N = \frac{100(Tm-To) \times Ho}{(Tag-Tm)Hag + (Tm-To)Ho - \%as \times Has(Tm-Tas)}$$

Where:

N is the percent by weight of the total (old material plus new aggregate) that is new material.

Tag is the temperature of the new aggregate entering the pugmill.

To is the temperature of the old material.

%as is the percent asphalt to be added based on the weight of the new aggregate.

Tas is the temperature of the asphalt.

Tm is the desired mix temperature.

Has is specific heat of asphalt.

Ho is specific heat of old material.

Hag is specific heat of aggregate.

For example, assume the dryer can heat the aggregate to the temperature necessary for the material to reach the pugmill at 400F, a mix temperature of 325F is wanted, the old mix has a temperature of 70F, the new asphalt is at 275F, the asphalt content to be used is 5.5% of the new aggregate, specific heat of asphalt is 0.40, of aggregate is 0.23, of old mix is 0.24.

$$N = \frac{100(325 - 70) \times 0.24}{(400-325) \times .40 + (325-70) \times 0.24 + 5.5 \times 0.40(325-275)}$$

Operating the dryer at a higher temperature would permit the incorporation of more old material.

If the percent old material had been chosen instead of the dried aggregate temperature, the required temperature of the new aggregate could be computed as:

$$Tag = \frac{(100-N)(Tm-To)(Ho) + (\%as)N(tm-Tas)(Has)/100 + N(Tm)Hag}{N \times Hag}$$

For example, assume 60% new aggregate and 40% old material is to be used, the desired mix temperature is 325F, the old material will be 70F, the new asphalt is at 275F and that the asphalt to be added is 5.5% of the new aggregate.

$$Tag = \frac{(100-60)(325-70) \times 0.24 + (5.5x60)(325-275) \times 0.40/100+60x325x0.23}{60 \times 0.23}$$

Tag = 507 F

If this temperature is beyond the capabilities of the dryer, then 40% old material is too much. The percent new binder in the total binder can be computed as:

(% new) = (%as x N)(%as x N + %as old x (100 - n))/100

Where:

(% new) is the percent new binder in the total binder,

(%as old) is the percent binder in the material to be recycled.

This percent new material determines the character of the recycling agent needed. The first step would be to extract the asphalt from a sample of the old material, thus determining the percent of binder present. An Abson recovery would provide a small amount of the aged binder. As either the sliding plate of cone viscosimeter uses only a drop of asphalt, the residue from the Abson recovery when blended with different softer materials at several levels could be used for numerous viscosity tests. A plot of viscosity versus percent of the final binder which is new would have the shape shown as Figure III-1. A horizontal line through the viscosity of a sample made of 100% AC-20 would define all blends that meet the character of an AC-20 and the intersection with the curve for a particular softening agent determines the amount of that material required. Entering this value into the last equation above for percent of new material in the total binder and solving for N gives a limiting value for the amount of recycled mix which can be new material. Substituting this value for N in the earlier equation for aggregate temperature determines the temperature of new aggregate required.

As a last example, assume the asphalt content of the old material is 6.0%, the viscosity of various blends of soft asphalt and the old binder is shown by Figure III-1. The amount of old material that can be included if AC-5 is used for recycling is found after determining AC-5 level to be used from Figure 6, by substituting in the last equation above and solving for N.

25% = (5.5xN)(5.5N + 6.0(100-N))/100

N = 27%

The temperature to which the new aggregate must be heated is found as:

$$Tag = \frac{(100-27)(325-70).24 + 5.5x27(325-275).40/100 + 27x325x.23}{27 \times .23}$$

Tag = 1049F

The dryer can not operate at this temperature and a greater amount of new material must be used. Using AC-10, the level of new asphalt, from Figure III-1 would be 65% and the percent of new aggregate would be:

65% = (5.5xN)(5.5N + 6.0(100-N))/100

N = 67%

$$Tag = \frac{(100-67)(325-70).24 + 5.5x67(325-275).40/100 + 67x325x.23}{67 \times 0.23}$$

Tag = 460F

This temperature is within the plant capacity. A suitable mix would then be:

| | |
|---|---|
| 67% New Aggregate | 1285 pound/ton |
| 33% Old pavement | 634 pound/ton |
| 6% of 67% AC-10 | 81 pound/ton |

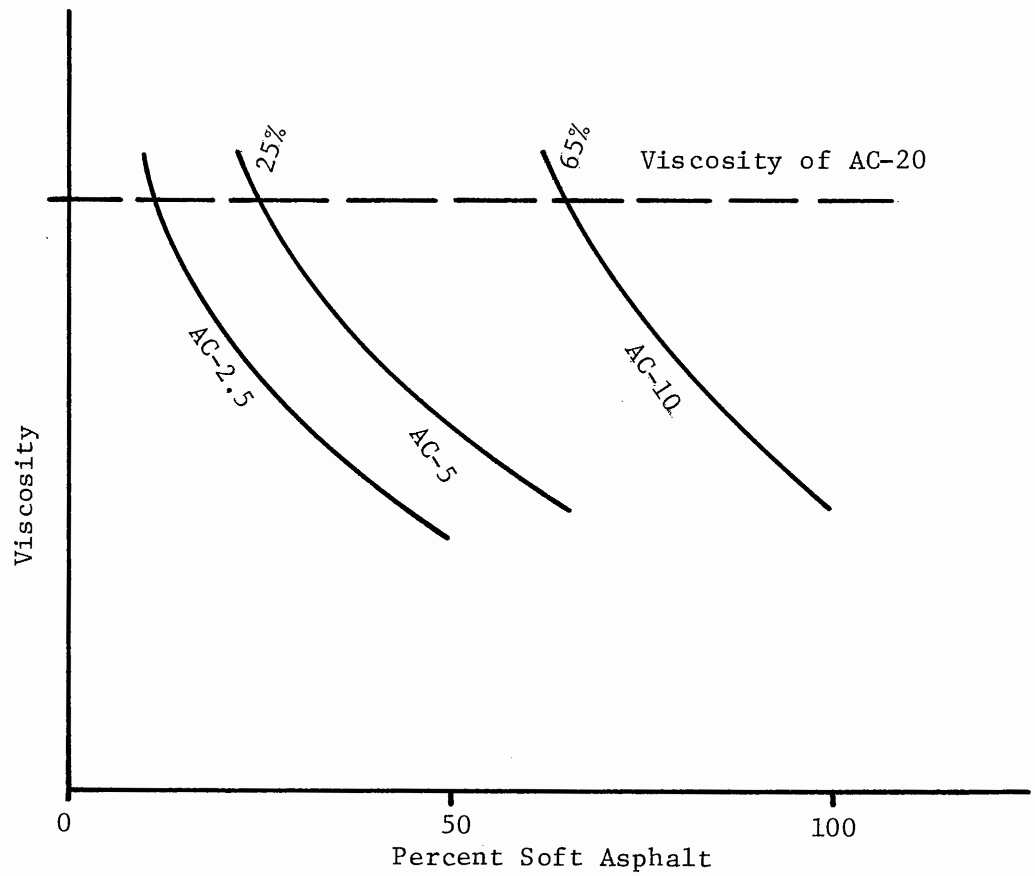


FIGURE III-1, Viscosity of Blends of Soft Asphalts and Aged Binder