A STUDY OF RECYCLING FEASIBILITY

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16. Abstract

This report describes a feasibility of recycling asphalt pavements using two major analytical techniques: High Performance Gel Permeation Chromatography (HP-GPC) and Dynamic Mechanical Analysis (DMA). HP-GPC probes the chemistry of the asphalt cement. DMA measures certain physical characteristics of the asphalt cement and of the mix.

Four projects that had been recycled, three by hot methods, the other by a cold, in-place process (CIPR), were studied. Specifically, the HP-GPC characteristics of the asphalts before and after recycling and the resilient moduli of some recycled mixtures were obtained. In addition, three sources of recovered asphalt pavement were subjected to modeling of hot and cold recycling strategies and tested by DMA on mixes as well as by HP-GPC. Finally, an additional five pavements that are candidates for recycling were sampled and the asphalt cements extracted for HP-GPC and DMA testing using both hot and recycling simulations. This report details the study procedures and discusses the data and their interpretations.

Included in this report is data on the HP-GPC characteristics of the asphalt cements available in the state of Montana in 1993. Also, testing of asphalt cements from an experimental project and a distressed pavement is addressed briefly.

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DISCLAIMER STATEMENT

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ABSTRACT

This report describes a study of the feasibility of recycling asphalt pavements using two major analytical techniques: High Performance Gel Permeation Chromatography (HP-GPC) and Dynamic Mechanical Analysis (DMA). HP-GPC probes the chemistry of the asphalt cement. DMA measures certain physical characteristics of the asphalt cement and of the mix.

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Included in this report is data on the HP-GPC characteristics of the asphalt cements available in the state of Montana in 1993. Also, testing of asphalt cements from an experimental project and a distressed pavement is addressed briefly.

EXECUTIVE SUMMARY

This report describes the study of the feasibility of recycling asphalt pavements using two major analytical techniques: High Performance Gel-Permeation Chromatography (HP-GPC) and Dynamic Mechanical Analysis (DMA). HP-GPC probes the chemistry of the asphalt cement. DMA measures certain physical properties of the asphalt cement and of asphalt/aggregate mixtures.

Four projects that had been recycled previously, three by hot methods, the fourth by a cold, in-place process (CIPR), were studied. Results from the hot recycled materials indicate that the chemical characteristics of the asphalt cement are not seriously damaged by the heating required. However, there is also little evidence that these characteristics have been improved in the instances studied. In one of the hot, in-place recycling (HIPR) projects, an asphalt with poor performance characteristics was found. Resilient moduli of cores from this project are quite high and suggest that brittleness may be a problem. Resilient moduli of cores from the other HIPR project are in a good range. Thus, it may be that certain asphalts are not good candidates for recycling, at least with high ratios of salvaged material. The researchers urge MDT to monitor the performance of these pavements closely.

Only one CIPR project was included in the study. Performance results indicate that CIPR with an overlay of new hot mix is preferable to full reconstruction and much better than a simple overlay on the old pavement.

Three sources of recovered asphalt pavement (RAP) were subjected to modeling of hot and cold recycling strategies and tested by DMA on mixes. Results are encouraging for the effectiveness of hot recycling, but more guarded for cold processes. Although the data looks favorable for some cold recycling models, it suggests potential durability problems for others.

An additional five pavements that are recycling candidates were sampled and the asphalt cements extracted. DMA analyses were conducted on these asphalts and on simulated hot and cold recycled asphalts derived from them. The mixtures all passed the SHRP specifications for PG-46, 52 and 58, but some failed at PG-64, indicating that some recycled mixes may be sensitive at higher pavement temperatures.

Included in this report are HP-GPC data on the asphalt cements available in Montana in 1993. These data suggest that, with one or two exceptions, asphalt quality is reasonably good. Although transverse cracking is probable as the pavements age, serious temperature sensitivity which results in very early cracking and, perhaps, in asphalt-associated deformation, is less likely. Nevertheless, asphalt quality is only one contributor to pavement performance, albeit an important one.

Testing of samples from the Dickey Lake experimental asphalt blending project shows that the blended and control asphalts are quite similar (by HP-GPC analysis) and are not likely to account for any differences in performance.

The Rogers Pass pavement was severely distressed after one winter and an investigation of possible causes for the problem included HP-GPC testing. No unusual characteristics were found.

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INTRODUCTION

There are at least two cogent reasons for recycling asphalt pavements: 1) recycling conserves valuable resources, both asphalt cement and aggregate, and 2) recycling avoids the problems associated with disposal of asphalt pavement that must be removed from the roadway.

It is clear that recycling would be preferable, if one could be reasonably certain that a good quality pavement would result. In this project, we have tried to shed some light on this dilemma. First, we have done some testing on pavements that have already been recycled (Great Falls-North, Superior-East and West, Potomac-East, and Hobson-Utica). Second, we have investigated a number of samples from salvaged pavement stockpiles and from pavements that are candidates for recycling. Third, we have examined the foreseeable environmental effects of stockpiled or otherwise exposed salvaged pavements. (A report on the environmental ramifications was submitted previously.)

In addition, we will take this opportunity to report formally on three other topics: the characteristics of asphalts available in Montana in 1993, asphalt samples from the Dickey Lake asphalt blending project, and samples from a problem pavement at Rogers Pass.

BACKGROUND

Two advanced techniques will be used in evaluating samples in these studies: HP-GPC (High Performance Gel-Permeation Chromatography) and DMA (Dynamic Mechanical Analysis). HP-GPC has, by now, a long history of use for asphalts beginning with work done by Traxler in the 70's and continuing with research in this group sponsored by the Montana Department of Transportation (MDT) and the Strategic Highway Research Program (SHRP). A review of publications on the subject until 1990 was produced for SHRP (1), therefore, an extensive review will not be attempted here. However, a few comments are in order, particularly since our GPC techniques have changed somewhat as a result of our SHRP work.

· GPC separates the molecules in a mixture according to their size.

· The molecular size distribution of an asphalt is related to its performance, particularly with regard to transverse cracking.

· The best performance found in Montana is represented by an asphalt recovered from a pavement that served for more than 30 years without cracking. This model was used to predict successfully the performance of asphalts used in the Big Timber Test Sections, constructed in 1983 (2), and was used both as an analytical model and for comparisons with other asphalts that will be discussed in this report.

· Two major changes in the analytical system resulted from the SHRP studies: the detector is now a multi-wavelength ultraviolet-visible instrument, instead of the single wavelength unit used previously; the brand of analytical column has been changed to take advantage of more efficient packing materials now available. Interpretation of the resulting data will be discussed further in the Experimental Section and details concerning the technique may be found in Appendix A.

Dynamic Mechanical Analysis (DMA) is a tool for the study of physical properties of asphalt. It received a great deal of attention from SHRP researchers and is now becoming familiar as part of SHRP asphalt specifications. In the specifications it is used on neat asphalt cement. However, at Oregon State University, the ideas have been applied to asphalt mixtures by Dr.Chris Bell and associates (3,4). In this form, DMA has a great deal of potential in predicting the performance of paving mixtures. Therefore, we were eager to obtain DMA analyses of some of the possible recycling mixtures in the current project. DMA procedures used on this project specifically will be outlined in Appendix B.

EXPERIMENTAL SECTION

HP-GPC

All asphalt mixes were extracted using tetrahydrofuran (THF), and all samples were analyzed according to our usual procedures (see Appendix A). Data available from these experiments can be viewed and interpreted in a variety of ways, only a few of which will be used in this study. Both simple and useful is the chromatogram at a single wavelength such as that at 340 nm shown in Figure 1. The absorption due to large molecules and/or intermolecular assemblies is recorded on the left with absorption due to successively smaller molecules (or possible assemblies) appearing to the right. Overlaying these chromatograms for different asphalts is useful for qualitative visual comparisons, including the comparison of an asphalt with the model.

Although no universal and absolute detection system is available for use in the GPC analysis of asphalts, the diode-array detector (DAD) provides a great deal of useful chemical information. After a sample is separated by apparent molecular size in the GPC column, the DAD analyzes the eluent by means of ultraviolet-visible spectroscopy in the range 200-600 nm. This takes advantage of the fact that molecules which are conjugated, including those which are aromatic (see Figure 2) absorb light in this range to give information about their structures. Details about this information are not necessary for this study, but it should be noted that we now have evidence that interactions among aromatic molecules are important in the composition and behavior of asphalts. These are in addition to the interactions among polar entities.

The diode array detector makes it possible to obtain data at a number of wavelengths in one experiment (5). Because these give more information about the chemical composition of the sample, we use seven chromatogram plots for quantitation by integration of the areas under the curves. These areas are divided into slices as shown in Figure 3. In this report, the following parameters will be used:

· Total conjugated volume, (CV_t)--the sum of areas under the seven chromatograms to assess the relative conjugated character of the sample. A larger value indicates that there is more conjugation in the molecules of a given sample.

· Percent conjugated volume, slice or segment ($\%CV_{x-y}$)--the percentage of CV_t represented between two elution times. $\%CV_{13.3-19.7}$ may be termed %LMS, percent large molecular size or assembled materials. As a result of the SHRP work, we are dividing the whole area under the curves into four segments, rather than the three which may be familiar. However, the %LMS remains most important.

These changes, although enabling us to obtain more information from a given sample, have made direct correlations with data obtained with older systems difficult. Thus use of the model asphalt is even more important. Throughout this report, the relationships between sample asphalts and the model will be emphasized.

Sample Selection

Samples were, with few exceptions, obtained and shipped to us by the Montana Department of Transportation (MDT). These included virgin asphalt cements available in the state during 1993, recovered asphalt pavement (RAP) samples to augment those obtained directly by us and cores from pavements at our request.

- 1993 Asphalt Cements:
  - Refinery A 85-100, 120-150 and 200-300
  - Refinery B 85-100, 120-150 and 200-300
  - Refinery C 85-100
  - Refinery D 85-100 and 120-150
  - Refinery E 85-100

- RAP samples from stockpiles:
  - Bowman's Corner
  - Elmo-West
  - Milligan Canyon

- cores:
  - Dawson County Line-East *
  - Fort Benton-North and South *
  - Great Falls-North
  - Hardy Creek-North *
  - Hobson-Utica (before and after HIPR)
  - Lothair-East *
  - Malta-Saco *
  - Potomac-East (before and after HIPR)
  - Superior-East and West

- Additional samples at MDT request
  - Dickey Lake
  - Rogers Pass

Dynamic Mechanical Analysis

Mixture studies using DMA concentrated on three RAP sources: Milligan Canyon, Bowman's Corner and Elmo-West. Several alternative recycling strategies were explored for each of these and will be further explained in the next section of this report. The specific procedures used in Dr. Bell's laboratory for this project are described in Appendix B.

DMA procedures for neat asphalts were used to test the effects of two recycling strategies on materials from the cores marked * in the list above. The cores were extracted and part of the extract was mixed with Recycling Agent I in an amount equal to 0.2% of the mix by weight to simulate a cold-recycling process. Also, some of the extract was mixed with 0.2% Recycling Agent I and enough Refinery B 85-100 to make a 50:50 mixture with the salvaged asphalt then heated at 150^{0} C. for 20 minutes in a simulation of hot recycling. The resulting samples were analyzed by SHRP DMA procedures.

RESULTS AND DISCUSSION

1993 ASPHALT CEMENTS

In previous work for MDT, we had tracked the HP-GPC characteristics of available asphalt cements because these characteristics are important to pavement performance (6). (In brief, for asphalts used in Montana, substantially higher LMS contents than found in the Montana model are associated with long-term transverse cracking whereas substantially lower LMS amounts have been associated with temperature sensitivity and a tendency to crack under thermal shock.) However, since our last analyses, at least two of the refiners had made changes. Therefore, we requested samples of all available asphalt cements during the 1993 paving season. HP-GPC data is given in Table 1; chromatograms of 85-100 grade asphalts are compared in Figure 4. The chromatogram for the model asphalt is included in this figure (and in others later in this text). Note that the model is a finished asphalt; asphalt cements will always undergo a small (2-3%) increase in LMS during hot mix processing. Thus, to match the model, one would prefer an untreated asphalt cement to have slightly less LMS material than the finished model.

Asphalts from Refinery B have indeed changed substantially. They now contain more LMS material and are no longer likely to be so temperature sensitive as to be subject to early cracking failure. (We have found that temperature sensitivity is often associated with very low LMS content.) It seems that the grade is being determined at the vacuum tower (ie., these appear to be "straight run" products) as evidenced by the fact that the harder asphalts contain more LMS material (Figure 5), but all grades are similar in CV_t. When the amount of LMS is increased during the hot mixing process, the percentage may be somewhat higher than desired to fit the model, but transverse cracking is likely to occur more slowly and to be less severe than was observed with the older Refinery B product in the Test Sections, for example (2).

Only one grade of asphalt was obtained from Refinery C (Figure 4). It contains a somewhat higher percentage of LMS material than in previous years and hot mix processing may push it slightly above the desirable limit. It may, therefore, not perform quite as well, in the long term, as the Refinery C product in the Test Sections. That is, it may develop transverse cracks slowly.

Products from Refinery A continue to pose some questions. Chromatograms in Figure 6 and data in Table 1 show that the three grades differ not so much in percentage of LMS but rather in CV_t and shape of the molecular size distribution curves. The 200-300 grade contains more non-conjugated material that does not absorb within the range of our detector (thus the lower value for CV_t) and so can not be further described. The 120-150 grade has a slightly lower apparent LMS percentage than either of the other grades, but the chromatograms in Figure 6 reveal that it actually contains a substantial amount of LMS material. The percentage is skewed by the highly aromatic material on the opposite side. Comparison of the seven chromatogram plot of the 120-150 asphalt in Figure 7 with that of the 85-100 grade in Figure 8 makes this characteristic obvious. Similar characteristics have been observed in the past. Unfortunately, the performance of this type of material has not been particularly good, as demonstrated in the Test Sections (2). Also, an asphalt of this type was found when we investigated a material that failed a loss-on-heating test for MDT about 1987. Thus, we remain somewhat skeptical of this type of asphalt. Nevertheless, Refinery A's 85-100 grade asphalt sampled in this study is quite similar to the Refinery C asphalt described above and is likely to produce similar results in the field.

Two grades of asphalt from Refinery D seem to be similar when compared by 340 nm chromatograms as in Figure 9. However, Refinery D apparently used a process similar to that of Refinery A in preparation of its 120-150 grade asphalt, although the effect is much smaller and is obvious only at shorter wavelengths in the 7-chromatogram plot. Its 85-100 grade asphalt is comparable with those from Refinery C and Refinery A discussed above.

Refinery E is a new asphalt source to us. The asphalt contains the most LMS material of these samples (Figure 4). It will probably crack slowly, but may produce more transverse cracks with time than the 85-100's from Refinery C, Refinery A and Refinery D.

In general, the asphalts available in 1993 are likely to perform quite well, all other factors being equal. We do, however, urge the MDT to pay attention to the performance of its pavements with the asphalt source and grade as key variables. We also caution that, without continued monitoring, the quality of future asphalts will be unknown until demonstrated in pavement performance.

DICKEY LAKE EXPERIMENTAL PROJECT -- F5-4(7)160

The Dickey Lake project grew out of the success of Section 13 in the Big Timber Test Sections (2). Asphalt cement in that section was a blend of Refinery B and Refinery

D asphalts designed to match the HP-GPC model. During the nine years of our observation of the Sections, this pavement did not crack, although sections paved with Refinery B or Refinery D asphalts individually did crack--Refinery B when less than a year old, Refinery D within three years of construction. Thus, about 1987, we suggested blend ratios to match the model using then-current samples of each of the Montana refiner's products to be used in a series of experimental projects. Two of these were eventually constructed: Darby-North and South, and Dickey Lake-North and South. Samples were submitted for HP-GPC analysis only from the latter pavement and only after construction had been completed.

For various reasons, MDT elected to use a 50:50 blend of asphalts from Refinery D and Refinery B for the experimental portions instead of the ratios recommended, and only Refinery D asphalt for control sections. Nevertheless, sample analysis shows that the asphalts supplied did not have the same HP-GPC characteristics as those used when blend ratios were recommended (see above discussion on 1993 asphalts and the explanation below). The project was constructed in three portions in 1989 and 1990. Unfortunately, because the paving could not be completed continuously, additional variables may have been introduced which will make it necessary to interpret performance results with caution.

Table 2 contains the results of HP-GPC testing. The asphalts, both blended Refinery B/Refinery D and Refinery D alone, are quite similar and are not likely to account for differences in performance. Variations in the values probably arise from slight differences in the asphalts shipped during each of the construction intervals and from experimental error. The only peculiarity noted here is in one of the blend chromatograms, shown in Figure 10. Because we do not have samples of the original asphalts for this site, we can not account for the source of the absorption at shorter wavelengths about 27.5 minutes. Because it occurs in only one sample, it is probably of no concern unless unusual performance is noted near Sta. 1208+70 where this material was placed..

ROGERS PASS PAVEMENT DISTRESS

Fully reconstructed in 1993, the pavement on Rogers Pass was displaying serious alligator cracking and rutting by spring of 1994. Possible causes for these problems were being explored and we were asked to test the asphalt by HP-GPC as part of that inquiry. Although these results have been reported informally to MDT, they will be briefly summarized here.

HP-GPC data in Table 3 show some variation in the asphalt over the length of the project, but the differences are not great and there are no unusual characteristics. That is, there is nothing in this data to implicate the asphalt cement as a factor in the pavement failure.

COMPLETED RECYCLING PROJECTS

A. Great Falls-North, RF 10-1(5)3 PE

This project was originally constructed in 1947 and was repaired in 1987 using four different strategies. The performance was surveyed in August, 1993, at four sites corresponding to cores taken from each section.

· MP 6--section consists of old pavement plus 0.25′ of virgin plant mix overlay.
--there was minor rutting and some flushing through the chip seal. Full width transverse cracks at 10-20 foot intervals. Cracks had been filled.

· MP 8--section was fully reconstructed with 0.35′ of plant mix.
--very minor rutting, little flushing. Transverse cracks spaced 60-80 feet apart.

· MP 12--0.25′ of the original pavement had been recycled, cold and in-place (CIPR) using a high float emulsion, then finished with 0.35′ of new plant mix.
--minor rutting and more flushing at this mile post; transverse cracks very widely spaced.

· MP 17--0.35′ of CIPR with 0.25′ new plant mix.
--minor rutting and some flushing; transverse cracks spaced about 120 feet apart.

HP-GPC results show some differences between the recycled asphalt and that in the new plant mix (Figure 11 and Table 4). LMS percentage in the recycled asphalt averages 17.4% with 15.6% in the virgin mix. Both have more LMS material than the model. [Note that by analyzing extracted asphalt, we are assuming that a homogeneous blend of aged asphalt and recycling agent and/or virgin asphalt is produced in the recycling process. Whereas this may occur in hot recycling, it is much less likely in cold recycling.]

With regard to transverse cracking at the time of our survey, the section including MP 12 was giving the best performance, followed by the sections including MP 17, MP 8, then MP 6. Since the surface asphalt is the same in all cases, the differences must be accounted for by the construction design and method.

· At MP 6, cracks probably are reflected from the undisturbed original pavement. This argues forcefully against the use of a simple overlay on a cracked pavement.

· Performance at MP 8 can be regarded in this case as representing what may be expected from a 0.35′ pavement constructed with this particular asphalt (Refinery D). It is similar to that observed in the Big Timber Test Sections at the same age.

· The difference in performance between MP 12 and MP 17, since both have the same total pavement depth, probably results from the slightly thicker overlay at MP 12. It seems obvious that interrupting the cracks in the old pavement by recycling is a good strategy (compare the behavior at MP 6), as is keeping a greater overall pavement depth (compare MP 8 and MP 12). The quality of the new asphalt is such that <u>long-term</u> crack-free performance can not be expected, but of the alternatives used on the Great Falls-North project, CIPR plus virgin overlay is the better choice when only performance is considered.

B. <u>Potomac-East</u>, NH 24-1(37)16

Originally constructed in 1968, the Potomac-East pavement was severely cracked when observed in the spring of 1993 before it was repaired. The hot, in-place recycling (HIPR) process involved the following steps:

1) Heat and remove the top 1 inch of pavement;
2) Mix with recycling agent (0.25% Recycling Agent I, in this case) and windrow;
3) Heat and remove the second inch of pavement;
4) Mix with recycling agent, virgin precoated aggregate and windrowed material;
5) Place and compact.

We were concerned about the quality of the original asphalt, what effects heating that asphalt might have, the effects of the recycling agent and the quality and effects of the virgin asphalt. Thus samples were obtained so that each of these concerns might be addressed using HP-GPC. [Note: previous research has shown that excessively high temperatures can result in large increases in percent LMS and damage to the asphalt (7).]

Data in Figure 12 and Table 5 show that the high LMS content of the asphalt could have been a factor in the cracking of the original pavement. (Compare the chromatograms of salvaged asphalt and the model.) Heating this asphalt in the recycling process added little if any to the LMS percentage. At this point, Recycling Agent I had also been introduced into the mixture. Although the molecular size distribution of this recycling agent is quite small, it is used in very small quantities and so has little if any effect on the MSD of the asphalt. It does not appear to break up any intermolecular associations in the LMS material.

The virgin asphalt is of a type not observed by us in Montana in the past. It is a very high LMS material and we would expect it to perform poorly with respect to transverse cracking in this climate if used alone. Fortunately, it is also used in relatively small amounts and has little overall effect in this recycled mixture. Note, however, that the ideal MSD has considerably less LMS material than the recycled asphalt. Thus, we would expect transverse cracking to occur within a few years in this pavement.

Cores from the finished pavement were sent to Dr. Bell for Diametral Resilient Modulus testing; data are shown in Table 6. Dr. Bell classifies these data as being in a normal range, that is, they are comparable to data from virgin mixes.

C. <u>Hobson-Utica</u>, RTS 239-1(1)0

This pavement was recycled using the same equipment and procedure as used on the Potomac project. Hobson-Utica was constructed in 1962 and was <u>very</u> severely cracked by the time it was to be recycled. The chromatogram in Figure 13 shows that the original asphalt is a rather unusual material. However,we did have in our archives a similar asphalt which we believe to have been a product of Refinery B in the early 1960's. The archive material was also collected from a very badly cracked pavement. Thus, the performance record for such asphalt is poor.

Data in Figure 14 and Table 7 show that HIPR had little effect on the asphalt cement itself. Furthermore, the resilient moduli for the recycled cores (Table 8) are quite high. In Dr. Bell's view, a resilient modulus approaching 1000 ksi indicates that the material may be quite brittle and prone to cracking.

If it is assumed that any virgin asphalt and/or recycling agent is completely incorporated into the salvaged binder during the recycling process, could this asphalt be "corrected" to fit the model? The approximate MSD resulting from a mixture of only 40% RAP and 60% Refinery B 200-300 (data from 1993) is shown in Table 7 as "Hypothetical". Although this hypothetical binder does not match the model, it has less absorption in Area 4 than Refinery A 120-150 for 1993. Nevertheless, considering all the evidence, it seems likely that asphalts of the type found in the Hobson-Utica pavement are not good candidates for recycling unless very low ratios of RAP are used. We would anticipate cracking to recur in this recycled pavement within a short time.

D. Superior-East and West, IM-IR 90-1(117)43

Three pavement sections that were later to be involved in this hot, off-site recycling project were surveyed by this group as part of a rutting study in 1986 (8). At that time, the pavement was in good condition with respect to both cracking and rutting. However, some of the cores (specifically those taken about MP 46.9) were disintegrated, indicating stripping, especially in the plant mix immediately below the open-graded friction course (OGFC). Samples were archived and thus were available for comparison with the recycled asphalt.

In the repair project done in 1993, the open-graded friction course and 0.25' of plant mix were removed and discarded; the next 0.35' of pavement was salvaged and recycled. Thus, the RAP contained Refinery D asphalt originally placed in 1965 and shown by the solid line in Figure 15. The recycled mix included 50% RAP with new Refinery D 85-100. HP-GPC characteristics of the recycled binder are also found in this Figure. Although the recycled binder still has more LMS material than the model, its HP-GPC characteristics are better than those of the RAP.

HP-GPC area percentages in Table 9 indicate that experimental values for the recycled material are very close to those calculated for a 50:50 mixture of salvaged and virgin asphalt. This is reassuring because it suggests that, even allowing for variability in the salvaged material and in the hot recycling process, there is little damage to the salvaged material caused by the heating.

MODEL RECYCLING CANDIDATES

Three salvaged materials were selected for intensive study so that they could be used as models for recycling strategies. These included Milligan Canyon, Elmo-West and Bowman's Corner.

Milligan Canyon [IR 90-5(50)264] was constructed in 1979 using 120-150 asphalt from Refinery A. Our survey of this pavement for the 1986 Rutting Study (8) found little cracking and relatively minor rutting (7mm in the driving lane). However, by 1991, raveling and rutting were severe and the pavement was removed completely and stockpiled. The MDT report suggested that the failure mechanism was low asphalt content which, when complicated by absorption and oxidation, produced a very thin asphalt coating and raveling resulted. It was felt that subgrade deficiency contributed to rutting.

The stockpiled material included a fair amount of uncoated base aggregate, but the gradation was satisfactory (see Table 10). There was some variation in the asphalt characteristics from sample to sample in the stockpile (see Figure 16).

The history of the Bowman's Corner RAP is less clear, but it is thought to have come from the Rogers Pass area and to have been stockpiled about 1983. Asphalt characteristics from HP-GPC suggest that the asphalt was supplied by Refinery D. The aggregate gradation was satisfactory.

Pavement in the Elmo stockpile was salvaged from an open-graded friction course in 1989. This asphalt also appears to have come from Refinery D. A nearby source of aggregate was specified to be used when this material was to be recycled. MDT recommended hot recycling for this project using 40% RAP and 60% Foote's Corner aggregate with 4.2% 120-150 Refinery D asphalt. That design was followed for the hot recycle simulation in this work.

In each case, RAP samples were extracted for testing here. In addition, RAP was supplied to Dr. Bell along with virgin aggregate, virgin asphalt (Refinery B 85-100 and Refinery D 120-150), emulsified asphalts (CRS-2 and CRS-2P) and Recycling Agent I. Dr. Bell secured quantities of Recycling Agent II and Recycling Agent IIa. Asphalt content and HP-GPC data for the three RAP materials are given in Table 11. Hypothetical LMS percentages for 50:50 mixtures with virgin asphalt are included in this table. [Note that HP-GPC area percentages are easily calculated and have been experimentally verified. In making these calculations, it is assumed that temperatures in any recycling process are well controlled so that the asphalt is not damaged.]

Three recycling strategies were targeted:

- Hot recycling with sufficient additional asphalt and aggregate to produce a 50:50 mixture (except Elmo, for which MDT's design of 40 RAP:60 virgin was accepted).

- Cold recycling with CRS-2P using a nomograph developed by Rogge, et al.(9, 10) for designing the mix.

- Cold recycling with both CRS-2P and a recycling agent. Since Recycling Agent I is not compatible with emulsified asphalt, Recycling Agents II and IIa were tested and Recycling Agent IIa was selected as the better material for these purposes.

All mixtures were prepared at Oregon State University as outlined in Table 12. DMA testing was conducted on unaged and aged samples simulating hot recycling. Short term aging, STA, at 149^{0}C for 45 minutes was used in most cases. Mixtures simulating cold recycling were cured at 60^{0}C for 1 hour before they were compacted for testing. DMA test results are shown in Tables 13, 14 and 15.

Data in the first three columns in these tables are related to the temperature sensitivity of the mixes. E@-3 Hz is the complex modulus at low frequency and, since frequency and temperature are interchangeable in this test, also represents a high temperature response. At the same time, E@+3 Hz is the complex modulus at high frequency and low temperature. Thus, the slope over this range is a measure of the temperature susceptibility of the mix--a lower value predicts better performance. In general, differences among the slope values for the various mixes are not significant. However, there are some interesting points in the E@-3 Hz data for the two cold mix strategies for the Bowman's Corner RAP. These numbers are higher and indicate that the mixes are stiffer at low temperatures. This probably indicates the dominance of the aggregate. Graphical representations of the relationships between complex modulus and frequency for these mixes will be found in Figures 17-31. Figure 32 contains plots for a typical virgin asphalt mix for comparison with those for the recycling simulations.

The next parameter, the maximum phase angle, suggests the relationship between viscous behavior (approaching 90^{0}) and elastic response (approaching 0^{0}). One would expect the phase angle to be greater for rich, fresh mixtures. Phase angle values for the hot mix strategies for all three RAP sources are similar. More important, they are in the same range as virgin mixes being studied by Dr. Bell's group. A normal range is 40-45°. Much lower values imply that the mixes are more brittle and may be prone to raveling. Data for some of the cold mixes are encouraging because, although the phase angles are not so high as seen in the hot mix and thus do not indicate the same extent of "rejuvenation", they do not suggest very poor performance. However, some of the cold mix strategies do not fare so well. Phase angles for cold mixes with Bowman's Corner RAP are particularly low as are those for Elmo with CRS-2 and Milligan Canyon with CRS-2P. Graphs of the phase angle data are also included in Figures 17-31.

Complex moduli at three different temperatures are found in the next columns of Tables 13-15 and, in the final column, the resilient modulus from the Diametral test at 25°C. Resilient moduli from the latter test in the range 300-450 ksi are considered to be good; as mentioned earlier, values approaching 1000 ksi indicate that the mix may be too brittle. For these recycling simulations the resilient moduli tend to be somewhat high for the hot mix strategies and lower than desirable for the cold mix types. The "best" modulus data are found for samples with optimum density and asphalt content; low values probably arise from the dominance of the aggregate (which, by itself would have a modulus of 20-50 ksi) and indicate potential durability problems.

In summary, the data from DMA and Resilient modulus tests are particularly encouraging for the use of hot recycling strategies. The phase angle data indicates that the RAP's are being "rejuvenated" to near virgin material characteristics. Since HP-GPC data show that the high temperatures involved in either HIPR or hot,off-site recycling apparently do not damage the recycled asphalt chemically, hot recycling is a good choice. In addition, molecular size distributions calculated for these mixes show a little more LMS material than desirable, but they are acceptable. Further, since the asphalts in these RAP materials are typical of the asphalts to be found in the state, these results may have broader applications. There are, however, some exceptional asphalts (eg. Hobson-Utica) that are believed to be much more problematical. They can be found with HP-GPC or through a check of the original records for the candidate pavement to determine construction date and asphalt source, although the latter is less reliable than HP-GPC.

On the other hand, cold recycling cannot be recommended with blanket enthusiasm. Some of the mixtures have better characteristics than others, of course. For example, Elmo RAP with CRS-2P has a maximum phase angle only a little lower than typical virgin mixes and a resilient modulus within the "good" range. Data for others suggests that durability may be a problem. The state of Oregon uses cold recycled mixtures on many of its low-volume roads and gets generally satisfactory service from them (9, 10). Nevertheless, these pavements are always sealed to improve moisture resistance. Considering Montana's positive experience with the Great Falls-North project discussed earlier, this suggests that cold recycling is a viable approach if the projects are carefully selected, designed and constructed.

OTHER CANDIDATES FOR RECYCLING

Five additional paving sites were selected from several suggested by MDT personnel. Descriptions of these sites follow. Baseline information is contained in Tables 16 and 17 and in Figure 33.

<u>Dawson County Line-East</u> [IR 94-6(38)191] was suggested as a potential recycling candidate and cores were submitted. This was the only site we did not visit in person, however, so we do not have detailed knowledge of the present condition. Aggregate gradations are not remarkable; the asphalt is high in LMS material, but is not otherwise unusual.

<u>Fort Benton-North and South</u> [NH 10-2(19)20] is near the Great Falls-North CIPR project discussed earlier and is being suggested for CIPR as well. Original construction was in 1964 with reconstruction between 1973 and 1975. At that time, 0.25' of plant mix surfacing containing 6.3% Refinery D 120-150 asphalt and 1.5% flyash was placed. We surveyed the project, concentrating on three sites at which cores were taken: MP 25,31 and 36. Although there is some variation in severity, cracking is extensive throughout the project with almost all types of cracking evident. However, there is remarkably little deformation, in general. Some of the cracks are filled and there is a chip seal. The few patches do not appear to be a major impediment to recycling.

HP-GPC data shows that the asphalt cement is consistent throughout the project and high in LMS as is typical for older Refinery D products. For its age and pavement thickness, the extent of cracking is not unexpected. The aggregate gradation (obtained from MDT) appears to be satisfactory.

<u>Hardy Creek-North</u> [IR 15-5(84)248] is being considered for recycling primarily because of raveling and rutting, with stripping as the underlying problem. This roadway was constructed in 1979-80 and consists of 0.40' of plant mix base plus 0.35' of plant mix surface with 6.2% Refinery D 120-150 asphalt and an OGFC. At the sampling site, MP 264, major distortion that may best be described as severe shoving in

the outside wheelpath, was observed. Cores taken in the driving lane disintegrated, so cores from the passing lane were used for testing.

Unfortunately, well-matched control samples are not available, so samples from the adjacent south-bound lanes were substituted. The latter pavement has a somewhat different typical section than the north-bound lanes and was constructed at a different time, thus limiting its value as a control. These sample sites are:

· MP 249 SB--surface layer is distressed with some longitudinal cracking and some raveling but no transverse cracks.

· MP 262 SB--considerable surface distress with some longitudinal cracking, raveling and transverse cracks through the full depth of the pavement.

· MP 269.6 SB--"ordinary" rutting is more pronounced at this site than at other sites in the SB lanes or much of the NB lanes. There is some flushing and transverse cracks are spaced about 50 feet apart.

Although the samples are not directly comparable, aggregate gradations are similar at all four sites. Also, the asphalt cement is consistent and typical for an older Refinery D product. The extent of cracking in the projects, therefore, is not unexpected. Thus, there is nothing in our data to suggest a cause for the extreme behavior observed at MP 264 NB. Recycling might not solve the problem if it lies in the nature of the aggregate or in some other construction factor.

<u>Lothair-East</u> [F1-5(3)308], according to the 1991 Road Log, was constructed in 1946 using a road mix. The westernmost five miles were improved in 1960 and have a total of four inches of surfacing; the remainder has only two inches of pavement. This pavement could be recycled if the material is worth salvaging. Although the performance varies somewhat from site to site, the pavement is generally riddled with fine cracks in a "map" pattern and is rutted. Considering its age and thickness of the section, it is in remarkably good condition, however. It carries a lot of grain trucks which made observation hazardous. There are some lengthy patches which are of different material than the original pavement. None of these were sampled for us, but they should be considered if recycling is undertaken.

Aggregate gradations are consistent through the project but have 10.5% passing the 200-M screen even before the pavement is removed, so gradations may need adjustment. The asphalt is somewhat different at each coring site (see Figure 34), although all show high LMS content and the molecular size distributions are somewhat broader than the "typical" asphalt.

Malta-Saco [F142 11] is another old pavement being considered for recycling. It was constructed in 1967 using Diamond 100-120 asphalt. It displays slight rutting and serious cracking--transverse cracks at intervals of 5 to 15 feet and map cracking as well.

There is some variation in aggregate gradation at the sampling sites, but this is not likely to be a problem. The asphalt is consistent through the project but is very high in LMS material. This particular asphalt has a history of poor performance.

The asphalt cement was extracted from cores from these pavements and prepared for DMA testing on Oregon State University's Bohlin Rheometer according to SHRP protocols. Sample sets for each project consisted of the untreated extracted asphalt, a hot recycling simulation and a cold recycling simulation. Hot recycling was modeled by mixing the extracted asphalt with 0.2% Recycling Agent I (by weight of salvaged mix) and sufficient Refinery B 85-100 to make a 50:50 mixture with the old asphalt, then heating the resulting binder at 120°C for 20 minutes. Hypothetical HP-GPC data derived from this strategy is shown in Table 18. Cold recycling was simulated by mixing the salvaged asphalt with 0.3% Recycling Agent I (by weight of mix). Both of these strategies assume complete mixing of new and salvaged materials.

HP-GPC data calculated for 50:50 mixtures of these asphalts mentioned above (Table 18) show that all except Lothair would have more LMS material than desirable and thus would be likely to develop transverse cracks after several years.

Selected data from DMA tests are included in Table 19; complete results may be found in Table 20. Delta values (the phase angle) for the extracted asphalts do not vary greatly, especially when it is considered that they come from widely differing aged pavements. As cold or hot recycling simulations are applied, delta values change little, and in some cases, not at all. Differences among the extracted asphalts are more obvious when the complex moduli, G*, are considered. Dawson Co. Line-East and Malta-Saco have the lowest modulus values, Fort Benton and Hardy Creek-North the highest. G*sine delta is the parameter used as a standard in the SHRP specifications. The test temperature is related to the maximum in-service pavement temperature. In Table 20, each of the binders is rated, pass or fail, at the different test temperatures. Asphalts derived from the hot recycling strategies frequently fail at higher temperatures. Whether this is of consequence, of course, depends on whether pavement temperatures of 58 or 64°C (136 or 147°F) are reached in this state. Nevertheless, it does indicate possible sensitivity of recycled mixtures at high service temperatures.

CONCLUSIONS

Recycling of asphalt pavements is the focus of this report. Three projects that have been recycled previously by hot methods were studied. These indicate that the heating process has not caused significant chemical damage to the recovered asphalt. This is reassuring because it is known that excessive heating can damage asphalt. However, there is also little evidence for improvement of the chemistry. HP-GPC data suggest that transverse cracking will recur in these pavements. One HIPR project contains an asphalt with a particularly poor performance history that may not be worth recycling. Resilient moduli of cores from this pavement after recycling are quite high and suggest brittleness. Resilient moduli of cores from the other HIPR project are in a good range. We urge MDT to monitor closely the behavior of these projects.

In a project where four repair strategies were used, the observed performance of sections in which virgin hot mix was placed over CIPR mix was superior to that of a completely reconstructed section and far superior to that of a section which received an overlay on the intact aged pavement.

Three RAP sources were subjected to modeling of hot and cold recycling strategies and tested by DMA on mixes. Results are encouraging for the effectiveness of hot recycling, but more guarded for cold processes. Although the data looks favorable for some of the latter, it suggests potential durability problems for others. HP-GPC testing shows no unusual characteristics among these asphalts although all have high LMS contents; thus, use of the lowest LMS virgin asphalt available is suggested for recycling.

An additional five pavements which are recycling candidates were sampled and tested by DMA of their asphalt cements as well as hot and cold recycling simulations. The mixtures all passed the SHRP specifications for PG-46, 52 and 58, but some failed at PG-64, indicating that some recycled mixes may be sensitive at higher pavement temperatures. In one of these pavements, a very high LMS asphalt was found. This material, we believe, would require a low RAP content and a low LMS virgin asphalt for effective hot recycling.

Included in this report is data on the 1993 asphalts available in Montana. This data suggests that, with one or two exceptions, asphalt quality is reasonably good. Although long-term cracking is probable, serious temperature sensitivity that results in early cracking and possibly in asphalt-associated deformation is less likely.

Testing of samples from the Dickey Lake experimental asphalt blending project show that the blended and control asphalts are quite similar in molecular size distribution. Thus the asphalts are not likely to account for any differences in performance.

The Rogers Pass pavement was severely distressed after one winter and an investigation of possible causes for the problems included HP-GPC testing. No unusual characteristics were found that would suggest that the asphalt cement contributed to the failure

RECOMMENDATIONS

1) The authors recommend that all recycling projects done to date be considered to be informal research projects and that their performance be monitored on a regular schedule. Observed behavior should be compared with data given in this report and other information that,presumably, was gathered in the construction process. In light of data presented in this report, comparison of the Potomac and Hobson-Utica projects may be particularly useful.

2) MDT should select pavements for recycling with care. Asphalts with particularly high LMS content or those with unusual molecular size distributions might require a low RAP to virgin material ratio for successful recycling. It is understood that HP-GPC analyses are not so readily available now. But data has been accumulated on so many Montana asphalts that, using historical records about asphalt source, MDT may be able to make an educated judgement about the type of asphalt in a candidate pavement.

3) MDT should make full use of DMA in designing recycled mixes, much as Marshall testing has been used in the past. That is, test different ratios of salvaged to virgin material, different virgin asphalts and different recycling agents to determine the blend more likely to be successful.

4) MDT should conduct a cost/benefit analysis of CIPR options using the Great Falls-North project as a model. Performance differences in that project at the time of our survey would seem to justify using CIPR with a 0.25′ to 0.35′ overlay on a comparable roadway.

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Table 1. HP-GPC Characteristics of 1993 Asphalts						
Refiner	Grade	CV_t	%LMS	% area 2	% area 3	% area 4
A	85-100	27.0	10.4	38.2	41.1	10.2
	120-150	33.4	9.7	30.2	32.6	27.6
	200-300	24.8	10.4	37.5	42.2	10.0
B	85-100	27.2	12.0	37.8	39.9	10.2
	120-150	26.0	11.6	37.8	40.3	10.3
	200-300	26.5	8.0	32.9	45.6	13.4
C	85-100	28.0	10.6	37.6	42.0	9.8
D	85-100	26.6	10.6	40.2	39.5	9.6
	120-150	27.4	10.1	37.6	38.3	14.1
E	85-100	27.0	12.8	37.4	39.8	10.1
model (aged)		29.6	11.7	36.1	41.5	10.7

Table 2. HP-GPC Characteristics of Dickey Lake Asphalts							
Sample	Station	Mix	CV_t	%LMS	% area 2	% area 3	% area 4
212-145	792+40	Ref. D	25.6	11.9	38.1	38.1	11.9
212-146	846+30	Ref. D	26.3	11.2	38.1	38.0	12.8
212-147	949+00	Ref. D	25.3	10.4	38.7	40.6	10.2
212-148	997+20	Ref. D	24.9	11.0	38.7	40.1	10.1
212-149	1051+60	Blend	----	10.9	37.3	42.0	9.7
212-150	1102+70	Blend	26.1	9.1	37.6	42.8	10.4
212-151	1156+25	Blend	24.7	10.4	37.0	40.7	12.0

Table 3. HP-GPC Characteristics of Rogers Pass Asphalts						
Sample	Station	CV_t	%LMS	% area 2	% area 3	% area 4
242-1	553+76,T	26.2	12.6	40.0	38.3	9.2
242-2	,B	25.7	13.1	38.0	37.2	11.7
242-3	674+91,T	22.2	11.2	36.8	43.1	8.9
242-4	,B	25.2	12.7	39.7	38.2	9.1
242-5	712+17,T	25.8	12.7	39.8	37.9	9.6
242-6	,B	25.6	12.3	39.8	38.5	9.5
242-7	758+48,T	25.8	13.2	39.6	38.2	9.1
242-8	,B	25.8	12.4	39.8	38.2	11.6
242-9	791+85,T	26.3	12.7	39.7	38.6	9.0
242-10	,B	26.3	12.2	39.5	38.6	9.8
242-11	832+98,T	25.3	13.2	39.9	37.4	9.4
242-12	,B	26.7	10.0	40.1	39.7	10.1
242-13	886+24,T	----	11.8	41.0	38.1	9.2
242-14	,B	25.7	11.9	40.8	37.8	9.0
242-15	954+38,T	24.9	12.7	40.6	27.6	9.0
242-16	,B	25.9	11.9	40.9	37.9	9.3
Average		24.0	12.3	39.7	39.7	9.6

Table 4. GPC Characteristics of Great Falls-N. Asphalts					
Sample	Mix	% LMS	% area 2	% area 3	% area 4
MP 12	CIPR	17.9	36.3	36.2	9.5
MP 17	CIPR	17.2	35.5	34.8	12.5
MP 17	NEW	15.6	38.7	35.0	10.7

Table 5. HP-GPC Characteristics of Potomac HIPR Asphalts					
Sample	CV_t	%LMS	% area 2	% area 3	% area 4
Original asphalt	26.7	15.1	37.7	38.0	8.9
Heated, + R.A. I	26.6	15.4	34.9	40.6	9.1
Virgin asphalt, precoat.	28.7	25.6	35.0	33.3	6.1
Final HIPR Product	27.2	16.0	36.6	38.6	8.7
Model	29.6	11.7	36.1	41.5	10.7

Table 6. Potomac HIPR Resilient Modulus Data		
Sample	Station	Resilient Modulus (ksi)
229-10	426+00	334
229-12	418+00	453
229-14	410+00	474

Table 7. GPC Characteristics of Hobson-Utica HIPR Asphalts					
Sample	CV_t	% LMS	% area 2	% area 3	% area 4
Before HIPR-ave.	39.6	14.0	26.2	33.4	26.5
Before HIPR, MP 8.75	---	15.6	26.0	33.0	25.2
After HIPR, MP 8.75	39.4	15.6	26.5	34.1	23.7
Hypothetical (see text)		11.0	30.1	40.6	18.1
Model (aged)		11.7	36.1	41.5	10.7

Table 8. Hobson HIPR Resilient Modulus		
Sample	Location	Resilient Modulus, ksi, 25^{o}C
224-15	MP 1.25	795
224-17	MP 8.75	921

Table 9. HP-GPC Characteristics of Superior Hot Recycling Samples					
Sample	CV_t	% LMS	% Area 2	% Area 3	% Area 4
MP 52.0- Ref. D, 1965	27.4	19.6	35.2	37.3	8.0
Ref. D 85-100, 1993	26.6	10.6	40.2	39.5	9.6
Recycled plant mix	27.4	15.4	37.2	37.6	9.7
Calculated recycled	---	15.1	37.7	38.4	8.8

Table 10. Milligan, Elmo and Bowman Aggregate Gradations							
Sample	% 1/2"	% 3/8"	% 4-M	% 10-M	% 40-M	% 80-M	% 200-M
Milligan	89.6	75.9	54.2	36.5	21.4	12.3	6.7
Elmo	98.6	96.1	61.5	31.9	18.0	13.0	9.8
Bowman	90	79	53	34	19	- -	6.7

Table 11. HP-GPC Characteristics of Milligan, Elmo and Bowman Asphalts							
Sample	%AC	CV_t	%LMS	%area 2	%area 3	%area 4	Calc. LMS
Milligan	4.6-4.8	28.8	14.8	36.8	35.5	12.6	13.4
Elmo	6.7	28.2	11.6	37.6	41.3	9.4	10.8
Bowman	6.2	29.1	14.4	32.6	39.7	13.3	13.2

Table 12. Mix Designs for DMA Testing					
Hot Mix Specifications					
Sample	% AC	RAP, g	New AC, g	New Agg, g	Treatment
Milligan	4.6	900	41	859	unaged, aged 149°C, 1 hr
Milligan	5.6	1100	51	649	"
Elmo	5.1	720	45	1035	"
Elmo	5.1	720	45	1035	aged 135°C, 4 hr
Bowman	4.6	900	41	859	unaged, aged 149°C, 1 hr
Cold Mix Specifications with CRS-2P					
Sample	Total liq.	RAP, g	Emulsion %/g	Water, g	Treatment (see also Appendix B)
Milligan	4%	1632	1.5/26.4	47.6	cured, 60°C, 1 hr
Elmo	4%	1632	(CRS-2) 1.2/20.4	47.6	"
Elmo	4%	1632	1.2/20.4	47.6	"
Bowman	4%	1632	1.8/30.6	37.6	"
Cold Mix Specifications with CRS-2P and Recycling Agent IIa (RA)					
Sample	Total liq.	RAP, g	Emul, %/g RA , %/g	Water, g	Treatment (see also Appendix B)
Milligan	4%	1632	0.7/11.9 0.5/8.5	47.6	cured, 60°C, 1 hr
Bowman	4%	1632	1.3/22.1 0.5/8.5	37.4	"

Table 13. DMA Data for Milligan Canyon RAP

	Trial	E@-3Hz	E@+3Hz	Slope	Max. Phase angle	E@5°C	E@25°C	E@40°C	Mod.,ksi
· DMA Test Results for Hot Mix with 4.6% asphalt (average voids-7.6%)									
unaged	1	1.60	3.30	0.28	41.4 @ -1.0 Hz	1450	555	108	485
	2	1.10	3.04	0.32	40.4 @ -1.0 Hz	876	252	100	512
	3	1.26	3.02	0.29	41.9 @ -1.69 Hz	1040	194	44	475
Ave.		**1.32**	**3.12**	**0.30**	**41.2**	**1122**	**334**	**84**	**491**
aged, 149°C, 45 min	1	1.45	3.21	0.29	42.0 @ -1.25 Hz	1640	348	84	586
	2	1.39	3.10	0.28	42.0 @ -1.75 Hz	958	206	77	579
	3	1.50	3.25	0.29	40.0 @ -1.25 Hz	1495	386	132	588
Ave.		**1.45**	**3.19**	**0.29**	**41.3**	**1364**	**313**	**98**	**584**
· DMA Test Results for Hot Mix with 5.6% asphalt (average voids-3.4%)									
unaged	1	1.65	3.38	0.29	44.7 @ -1.69 Hz	1547	479	109	532
	2	1.52	3.33	0.30	37.5 @ -1.25 Hz	1921	376	95	523
	3	1.32	2.96	0.27	40.7 @ -1.0 Hz	1629	306	82	468
Ave.		**1.50**	**3.22**	**0.29**	**41.0**	**1699**	**387**	**95**	**508**
aged, 149°C, 45 min	1	Data not available							546
	2	1.41	3.10	0.28	3.75 @ -1.25 Hz	1024	287	107	525
	3	1.55	3.25	0.28	37.5 @ -1.25 Hz	1629	306	82	493
Ave.		**1.48**	**3.18**	**0.28**	**37.5**	**1326**	**296**	**94**	**521**
· DMA Test Results for Cold Mix with CRS-2P									
cured, 60°C, 1 hr	1	1.80	3.30	0.25	27.5 @ -1.75 Hz	1502	318	102	176
	2	1.50	3.03	0.26	32.5 @ -1.0 Hz	678	270	68	182
	3	Data not available							157
Ave.		**1.65**	**3.17**	**0.25**	**30.0**	**1090**	**294**	**85**	**172**
· DMA Test Results for Cold Mix with CRS-2P and Recycling Agent IIa									
cured, 60°C, 1 hr	1	1.53	3.16	0.27	40.0 @ -2.6 Hz	1453	160	23	147
	2	1.61	3.39	0.30	35.0 @ -1.0 Hz	1887	474	72	189
	3	1.60	3.32	0.29	31.0 @ -1.5 Hz	2293	308	59	138
Ave.		**1.58**	**3.29**	**0.29**	**35.3**	**1878**	**314**	**51**	**143**

Table 14. DMA Data for Elmo RAP									
	Trial	E@-3Hz	E@+3Hz	Slope	Max.phase angle	E@5°C	E@25°C	E@40°C	Mod,ksi
· DMA Test Results for Hot Mix with 5.1% asphalt									
unaged	1	1.30	3.31	0.33	40.0 @ -1.25 Hz	1563	337	87	473
	2	1.50	3.30	0.3	41.0 @ -1.25 Hz	1621	398	68	480
	3	1.49	3.14	0.28	41.0 @ -1.25 Hz	1132	419	107	467
Ave.		**1.43**	**3.25**	**0.30**	**40.7**	**1439**	**385**	**87**	**470**
aged, 149°C, 45 min	1	1.56	3.05	0.25	37.5 @ -1.25 Hz	924	264	144	592
	2	1.51	3.32	0.30	38.0 @ -1.50 Hz	2260	380	113	532
	3	Data not available							642
Ave.		**1.54**	**3.19**	**0.27**	**37.7**	**1592**	**322**	**128**	**617**
aged, 135°C, 4 hr	1	1.30	2.86	0.26	40.0 @ -1.50 Hz	591	182	56	544
	2	1.31	3.00	0.28	40.0 @ -1.75 Hz	Not available			612
	3	1.40	3.17	0.29	37.5 @ -1.50 Hz	1602	308	76	495
Ave.		**1.34**	**3.01**	**0.28**	**39.2**	**1096**	**245**	**66**	**519**
· DMA Results for Cold Mix with CRS-2									
cured, 60°C, 1 hr	1	1.50	3.21	0.29	35.0 @ -1.50 Hz	1444	347	70	202
	2	1.47	3.22	0.29	36.0 @ -1.50 Hz	1157	377	62	234
	3	1.40	2.89	0.25	32.0 @ -1.50 Hz	717	168	74	259
Ave.		**1.46**	**3.11**	**0.27**	**34.3**	**1106**	**297**	**69**	**232**
· DMA Results for Cold Mix with CRS-2P									
cured, 60°C, 1 hr	4	1.38	2.88	0.25	37.0 @ -1.70 Hz	647	191	61	321
	5	1.40	3.18	0.30	40.0 @ -1.70 Hz	1110	372	127	302
	6	Data not available							285
Ave.		**1.39**	**3.03**	**0.27**	**37.2**	**878**	**281**	**94**	**303**

Table 15. DMA Data for Bowman's Corner RAP									
	Trial	E@-3Hz	E@+3Hz	Slope	Max.phase angle	E@5°C	E@25°C	E@40°C	Mod,ksi
· DMA Test Results for Hot Mix with 4.6% asphalt									
unaged	1	1.43	2.92	0.25	35.0 @ -1.5 Hz	650	194	65	464
	2	1.50	3.07	0.26	35.0 @ -1.5 Hz	725	265	80	426
	3	1.33	2.83	0.25	32.0 @ -1.5 Hz	553	142	52	453
Ave.		**1.42**	**2.94**	**0.25**	**34.0**	**643**	**200**	**66**	**448**
aged, 149°C, 45 min	1	1.54	3.20	0.28	37.0 @ -1.70 Hz	1364	386	112	599
	2	Data not available							606
	3	1.35	2.95	0.27	37.5 @ 1.70 Hz	794	229	61	561
Ave.		**1.44**	**3.07**	**0.27**	**37.2**	**1079**	**307**	**86**	**589**
· DMA Test Results for Cold Mix with CRS-2P									
cured, 60°C, 1 hr	1	Data not available							229
	2	1.8	2.95	0.19	23.0 @ -1.0 Hz	891	217	176	287
	3	1.64	2.87	0.21	26.0 @ -1.5 Hz	800	167	136	222
Ave.		**1.72**	**2.91**	**0.20**	**24.5**	**845**	**192**	**156**	**246**
· DMA Test Results for Cold Mix with CRS-2P and Recycling Agent IIa									
cured, 60°C, 1 hr	1	2.00	3.45	0.24	24.0 @ -0.5 Hz	3213	571	293	309
	2	1.86	3.29	0.24	26.0 @ -1.0 Hz	1747	428	113	259
	3	1.71	3.15	0.24	27.0 @ -1.2 Hz	1616	293	119	194
Ave.		**1.86**	**3.30**	**0.24**	**25.7**	**2192**	**431**	**175**	**227**

Table 16. Aggregate Gradations for Other Recycling Candidates							
Sample	% 1/2"	% 3/8"	% 4-M	% 10-M	% 40-M	% 80-M	% 200-M
Dawson	87.8	76.4	55.4	39.1	19.3	10.8	5.4
Ft.Benton	98.0	90.0	64.0	47.0	28.0	- - -	7.0
Hardy	95.0	82.4	58.9	41.2	22.5	12.6	7.3
Lothair	90.7	82.0	64.6	50.8	31.3	18.4	10.5
Malta	96.4	82.3	55.4	38.6	22.8	12.1	6.0

Table 17. HP-GPC Characteristics for Other Recycling Candidates						
Sample	%AC	CV_t	%LMS	% area 2	% area 3	% area 4
Dawson	5.9	28.1	15.2	38.2	38.1	8.4
Ft.Benton	6.3	27.3	16.8	36.6	36.5	10.1
Hardy	6.2	26.7	16.0	37.4	37.5	9.0
Lothair	5.9	29.7	11.3	28.3	41.9	18.5
Malta	6.1	28.1	19.0	36.0	35.2	9.8

Table 18. Hypothetical GPC Data for 50:50 Blends, Salvaged/Ref. B				
Sample	% LMS	% area 2	% area 3	% area 4
Dawson	13.6	38.0	39.0	9.3
Ft.Benton	14.4	37.2	38.2	10.1
Hardy	14.0	37.6	38.7	9.6
Lothair	11.6	33.0	40.9	14.3
Malta	15.5	36.9	37.5	10.0
Model (aged)	11.7	36.1	41.5	10.7

Table 19. DMA Test Results for Other Recycling Candidates						
Sample	Original extract		Cold Recycle Sim.		Hot Recycle Sim.	
	46°C	58°C	46°C	58°C	46°C	58°C
Delta at test temperature						
Dawson	84	87	77	83	86	87
Ft.Benton	71	78	75	82	81	86
Hardy	72	79	74	83	82	86
Lothair	74	81	77	84	84	87
Malta	79	84	79	84	84	87
G* at test temperature						
Dawson	5	1	26	4	8	2
Ft.Benton	55	11	26	5	14	3
Hardy	53	10	39	6	9	2
Lothair	34	7	20	3	4	1
Malta	10	2	13	3	4	1
G* sin delta at test temperature						
Dawson	5	1	25	4	8	1
Ft.Benton	52	10	25	5	14	3
Hardy	51	9	38	6	9	2
Lothair	33	7	20	3	4	1
Malta	10	2	12	3	4	1

Table 20. Summary of DMA Test Results for Other Recycling Candidates						
Sample	Temp., ^{0}C	G*	Delta	G*sin delta	Original	Aged
Dawson original	46	5.46	83.57	5.43	p	p
	52	2.81	85.15	2.8	p	p
	58	1.32	86.81	1.32	p	f
	64	0.62	87.79	0.68	f	f
Dawson cold recy. sim.	46	25.8	77.34	25.17	p	p
	52	9.92	80.92	9.80	p	p
	58	4.43	83.33	4.40	p	p
	64	2.07	85.21	2.06	p	f
Dawson hot recy. sim.	46	7.82	84.18	7.78	p	p
	52	3.02	86.00	3.01	p	p
	58	1.53	87.25	1.53	p	f
	64	0.74	88.41	0.75	f	f
Ft Benton original	46	55.4	70.99	52.38	p	p
	52	23.5	74.62	22.66	p	p
	58	10.6	77.66	10.36	p	p
	64	4.85	80.99	4.79	p	p
Ft. Benton Cold recy. sim.	46	26.3	75.4	24.45	p	p
	52	10.5	78.93	10.3	p	p
	58	4.66	81.69	4.61	p	p
	64	2.12	84.07	2.11	p	f
Ft. Benton Hot recy. sim.	46	13.8	81.27	13.64	p	p
	52	5.91	83.77	5.88	p	p
	58	2.67	85.66	2.66	p	p
	64	1.28	86.90	1.28	p	f

Sample	Temp., 0C	G*	Delta	G*sin delta	Original	Aged
Hardy original	46	53.3	71.89	50.66	p	p
	52	22.9	75.54	22.17	p	p
	58	9.57	78.75	9.39	p	p
	64	4.37	81.71	4.32	p	p
Hardy Cold recy. sim.	46	39.4	74.25	37.92	p	p
	52	20.00	76.20	19.42	p	p
	58	5.69	80.71	5.62	p	p
	64	2.79	83.37	2.77	p	p
Hardy Hot recy. sim.	46	9.44	81.69	9.34	p	p
	52	4.06	84.12	4.04	p	p
	58	1.86	85.95	1.86	p	f
	64	0.9	87.21	0.9	f	f
Lothair original	46	33.9	74.06	32.60	p	p
	52	15.1	77.26	14.73	p	p
	58	7.07	80.73	6.98	p	p
	64	3.08	83.5	3.06	p	p
Lothair Cold recy. sim.	46	20.2	77.50	19.72	p	p
	52	8.14	80.79	8.04	p	p
	58	3.37	83.59	3.35	p	p
	64	1.57	85.76	1.57	p	f
Lothair Hot recy. sim.	46	4.15	84.17	4.13	p	p
	52	1.82	85.88	1.82	p	f
	58	0.864	87.27	0.86	f	f
	64	0.421	87.93	0.42	f	f
Sample	Temp., 0C	G*	Delta	G*sin delta	Original	Aged

Malta original	46	10.1	79.22	9.92	p	p
	52	4.23	81.91	4.19	p	p
	58	2.14	84.01	2.13	p	f
	64	1.06	85.61	1.06	p	f
Malta Cold recy. sim.	46	12.6	79.48	12.39	p	p
	52	5.97	81.9	5.91	p	p
	58	2.81	84.32	2.80	p	p
	64	1.33	86.14	3.52	p	f
Malta Hot recy. sim.	46	3.54	84.37	3.52	p	p
	52	1.61	86.26	1.61	p	f
	58	1.53	87.25	1.53	p	f
	64	0.38	87.99	0.38	f	f

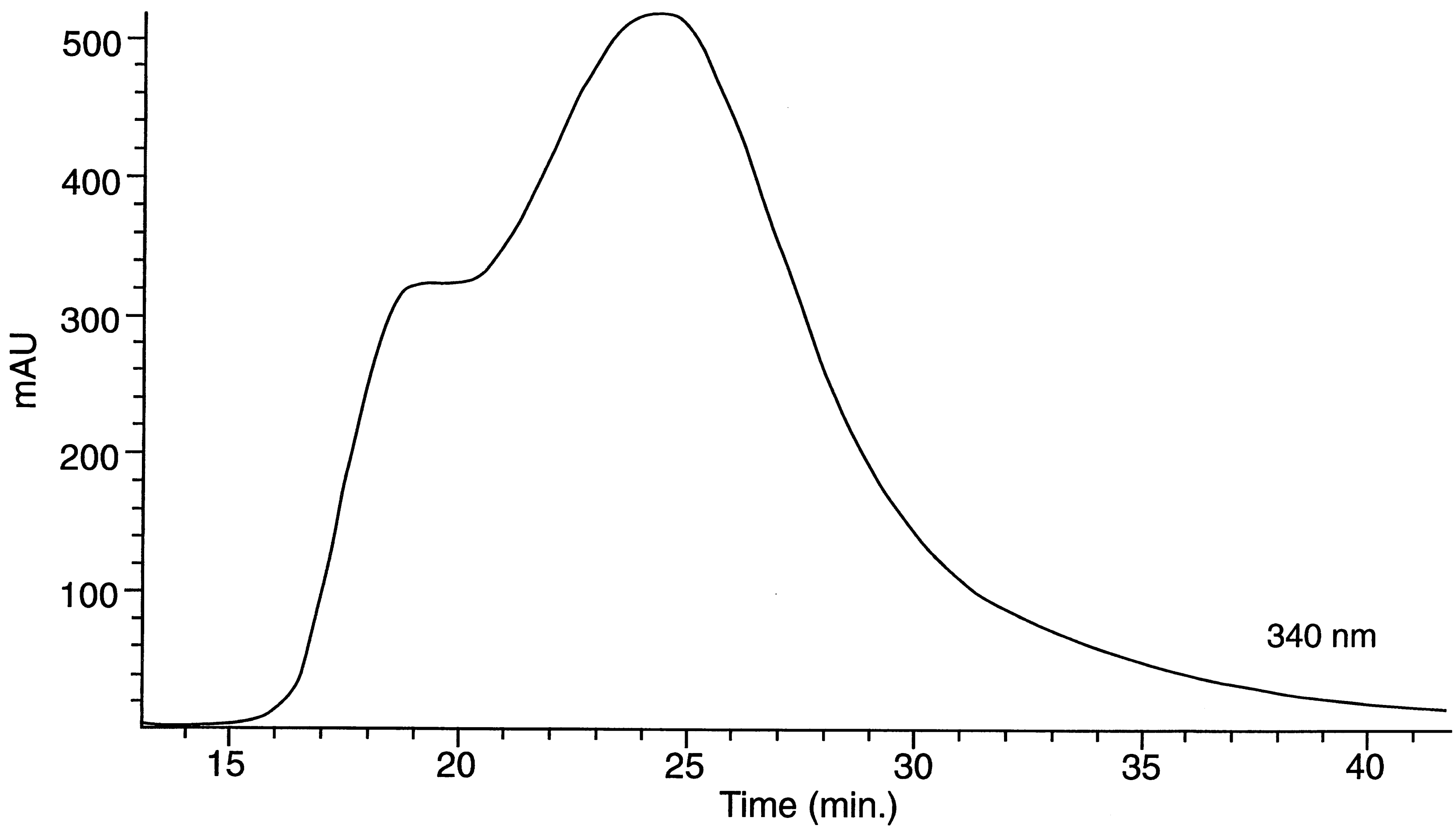
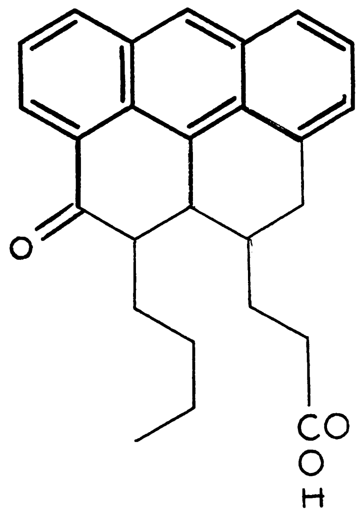


Figure 1. HP-GPC chromatogram of an asphalt at 340nm

Conjugated systems
(dark bonds)



--aromatic

--alicyclic

--aliphatic

--a functional group

Figure 2. Examples of functional group types.

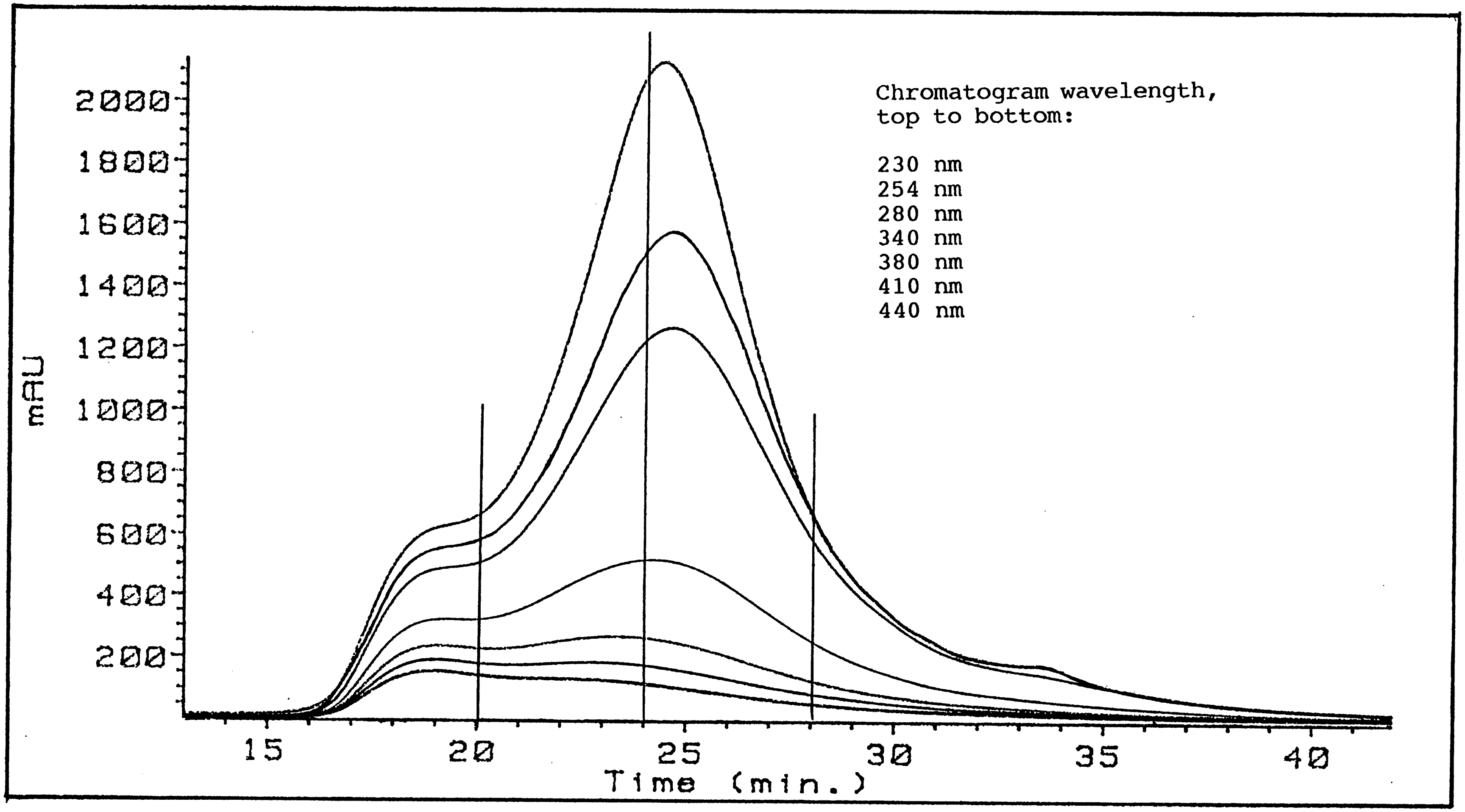


Figure 3. 7-Chromatogram plot of model asphalt

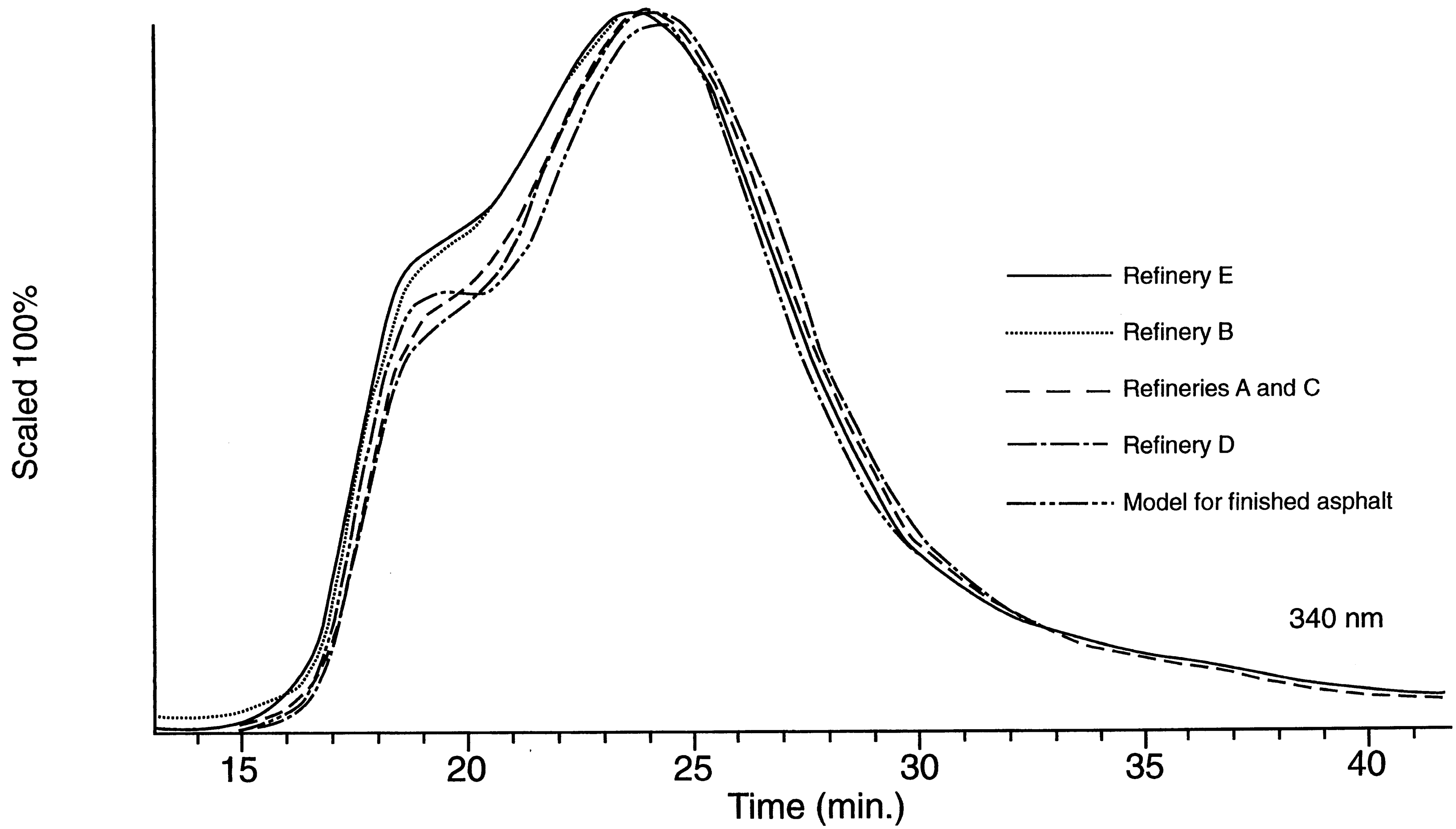


Figure 4. HP-GPC chromatograms of 85-100 grade asphalts provided in 1993.

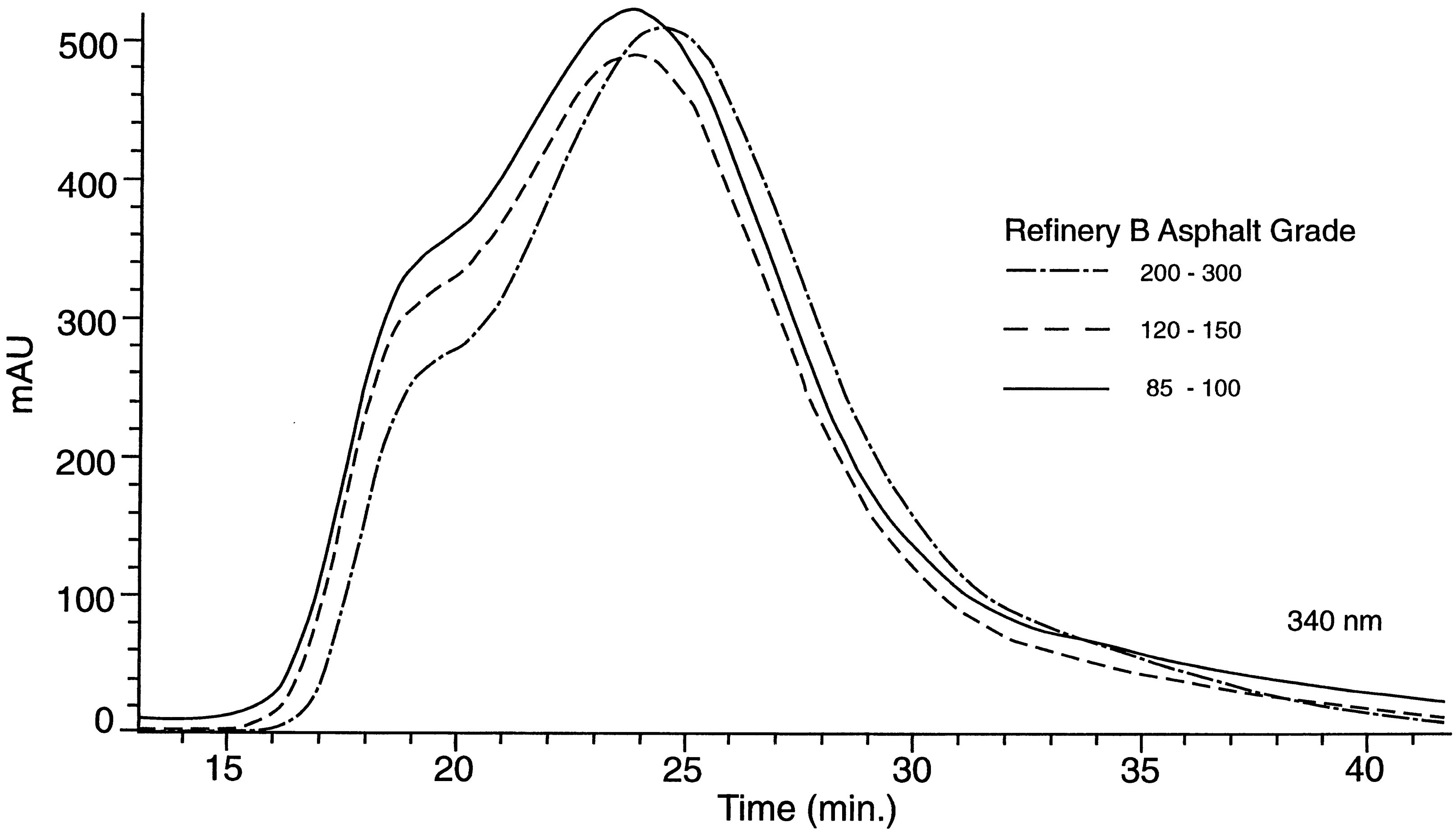


Figure 5. HP-GPC chromatograms of three asphalt grades from Refinery B, 1993

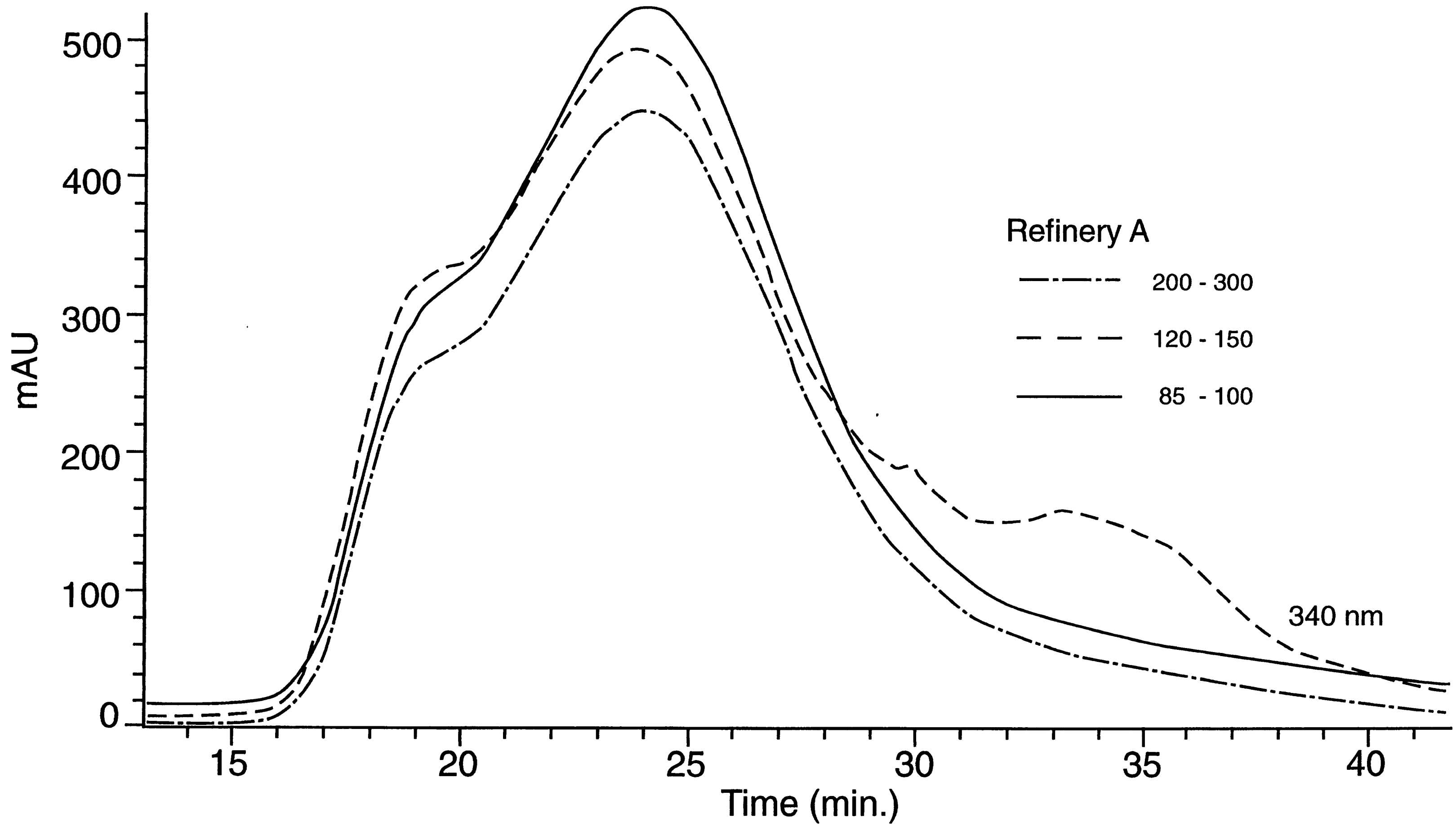


Figure 6. HP-GPC chromatograms of three asphalt grades from Refinery A, 1993

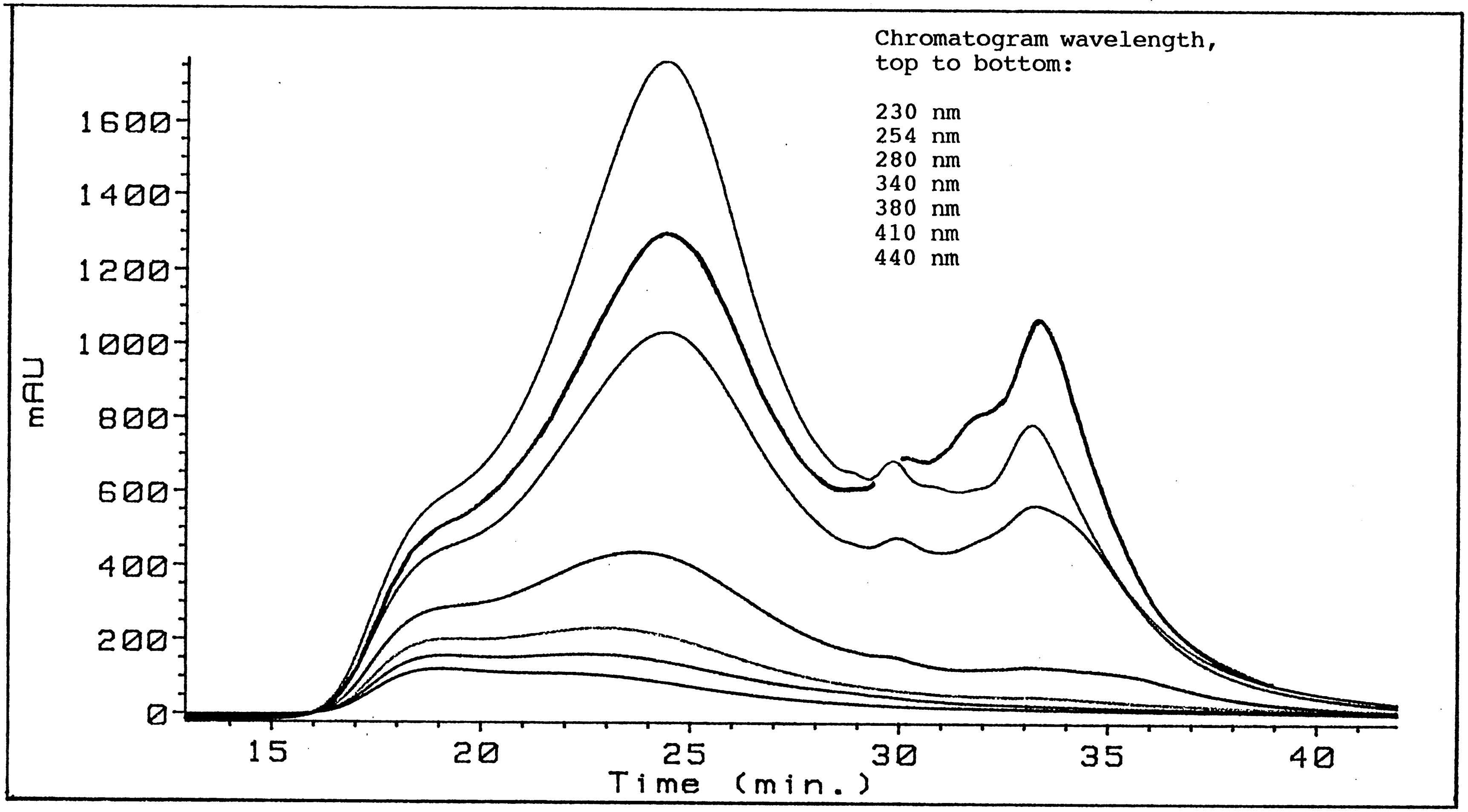


Figure 7. 7-Chromatogram plot of Refinery A / 120-150 Asphalt, 1993.

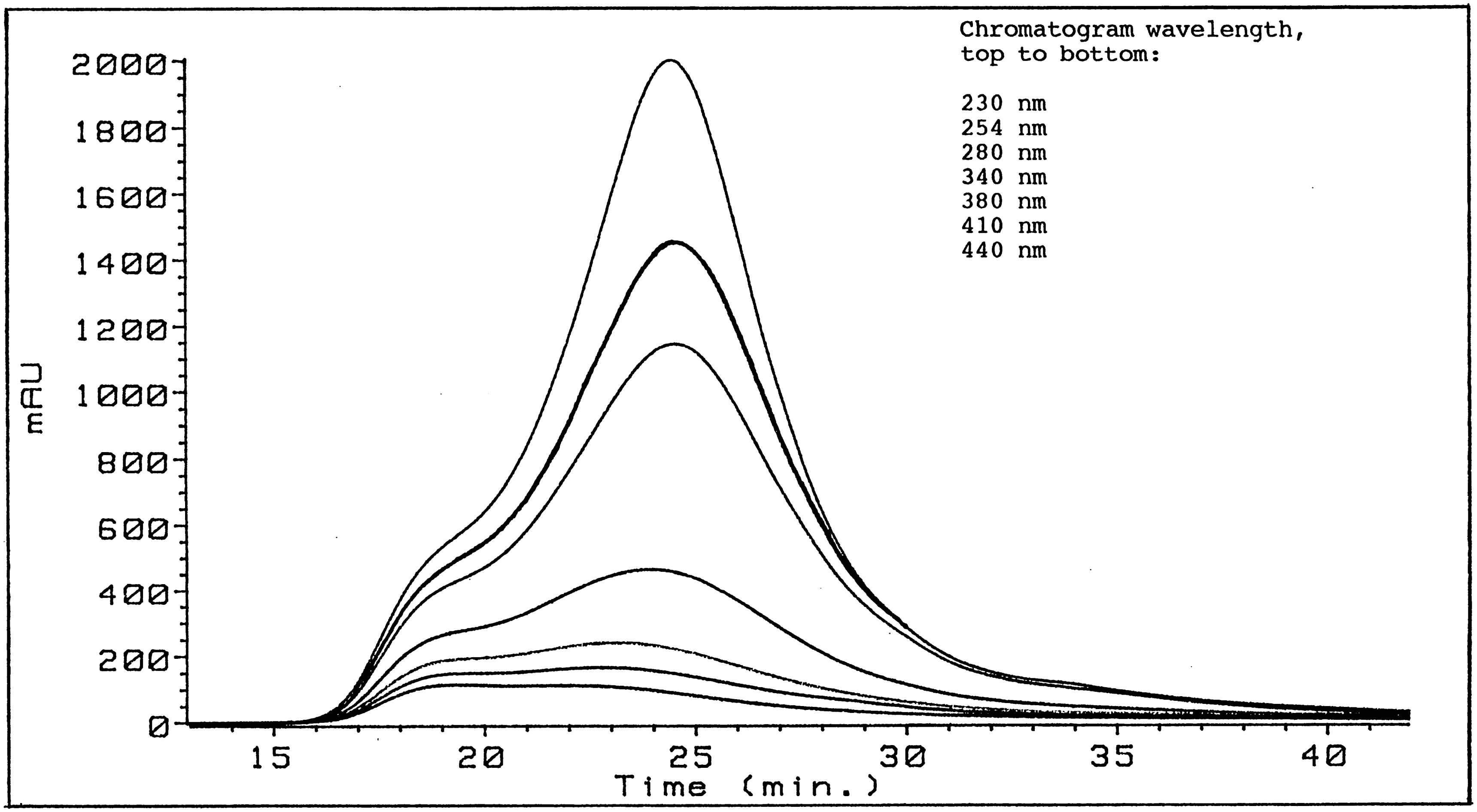


Figure 8. 7-Chromatogram plot of Refinery A / 85-100 Asphalt, 1993.

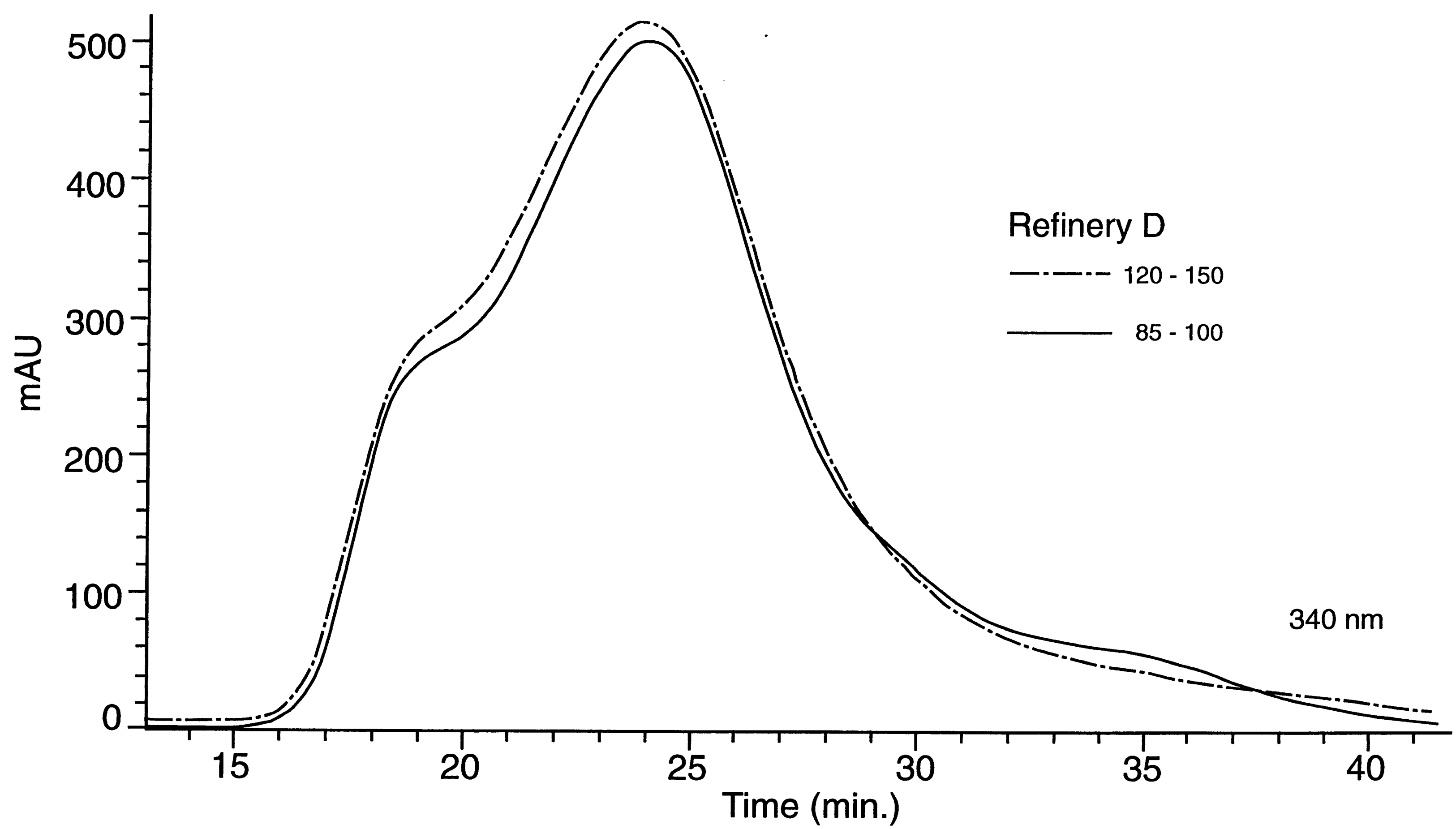


Figure 9. HP-GPC chromatograms of two asphalt grades from Refinery D, 1993.

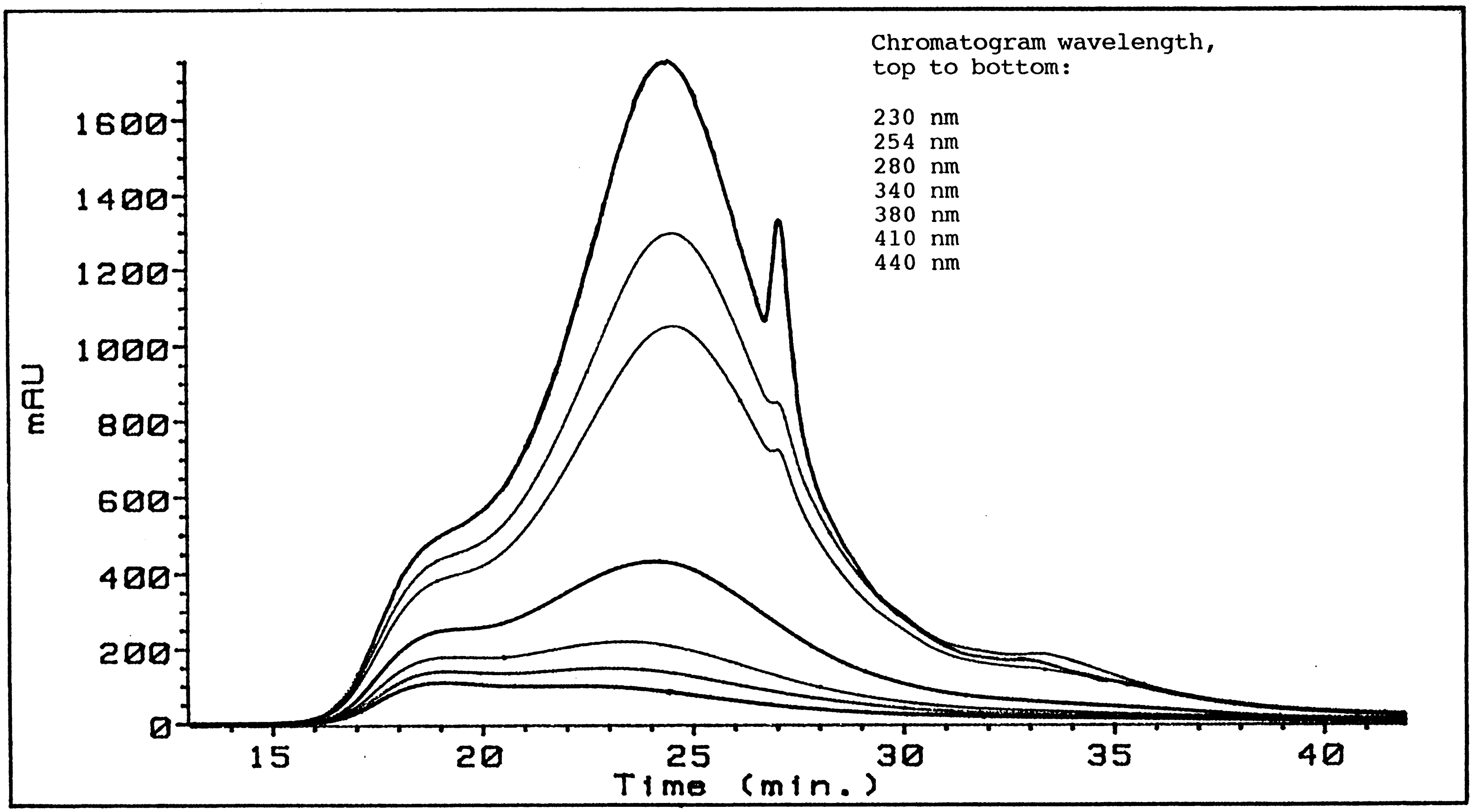


Figure 10. 7- Chromatogram plot of Dickey Lake, Refinery B / Refinery D Blend with unknown absorption about 27.5 minutes.

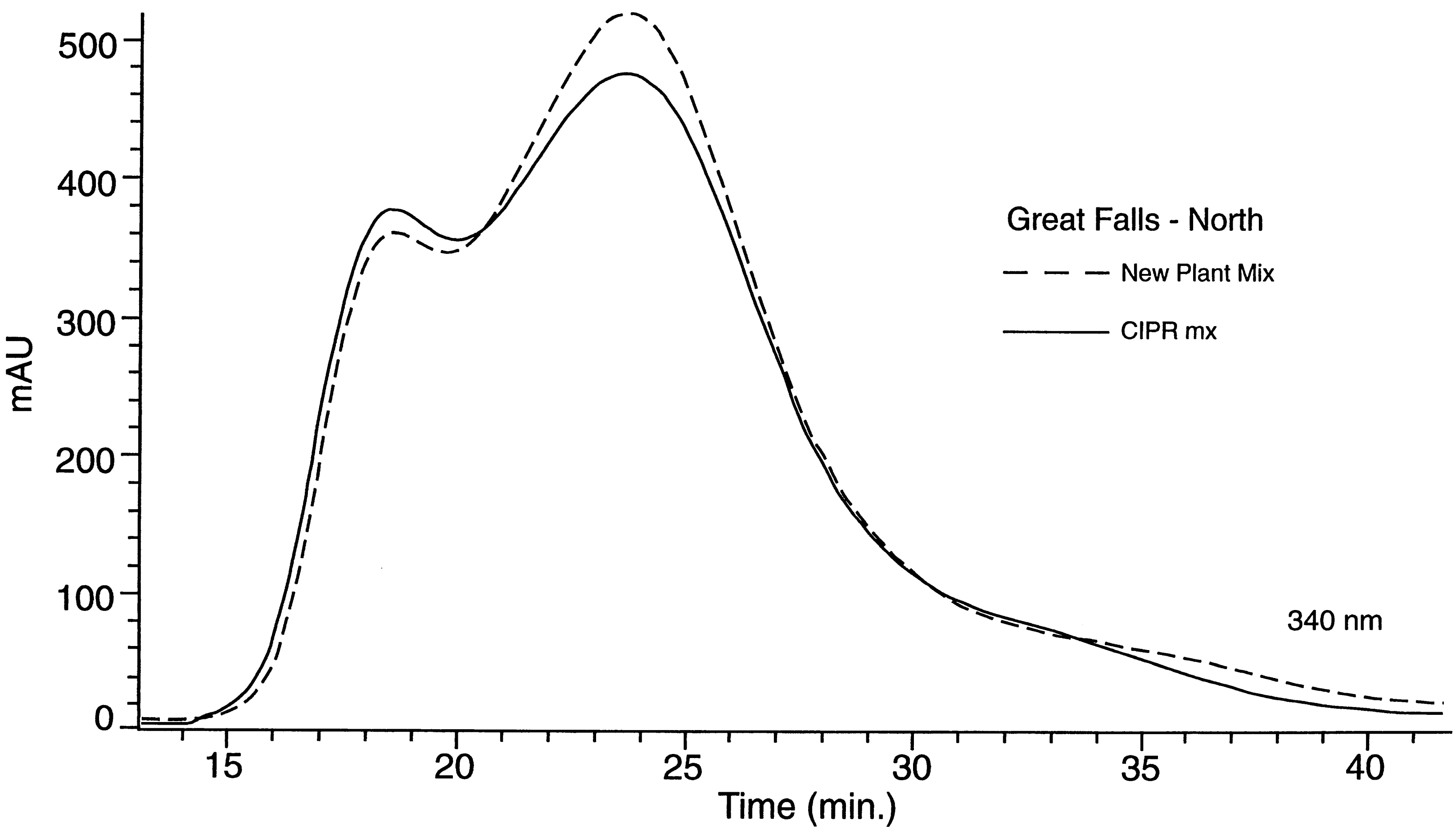


Figure 11. Comparison of HP-GPC chromatograms of new and cold, in-place recycled (CIPR) asphalt from Great Falls - North.

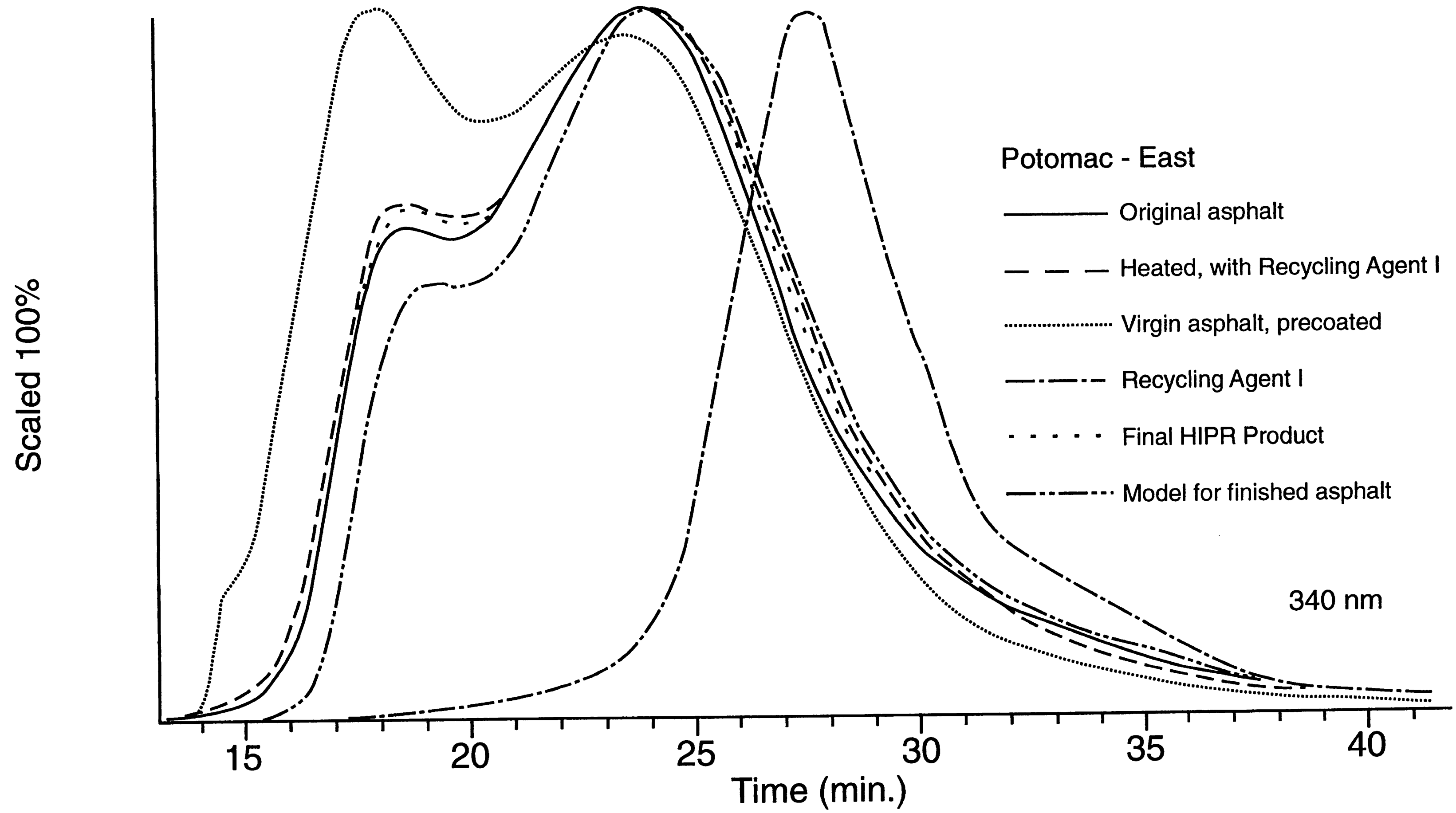


Figure 12. HP-GPC chromatograms of various materials in Potomac hot, in-place recycling (HIPR) Project

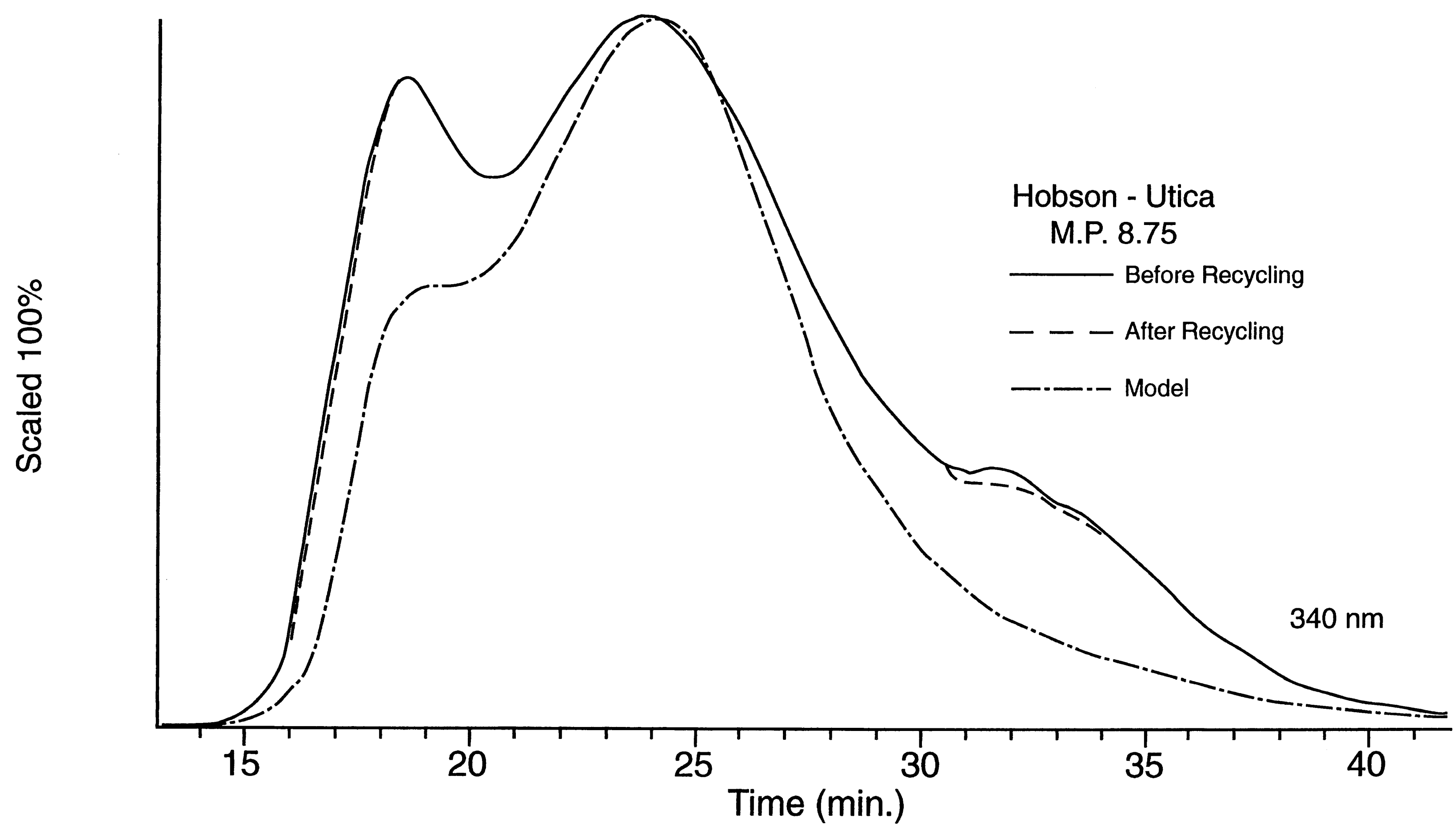


Figure 14. HP-GPC chromatograms of Hobson - Utica asphalt before and after hot, in-place recycling compared with model asphalt

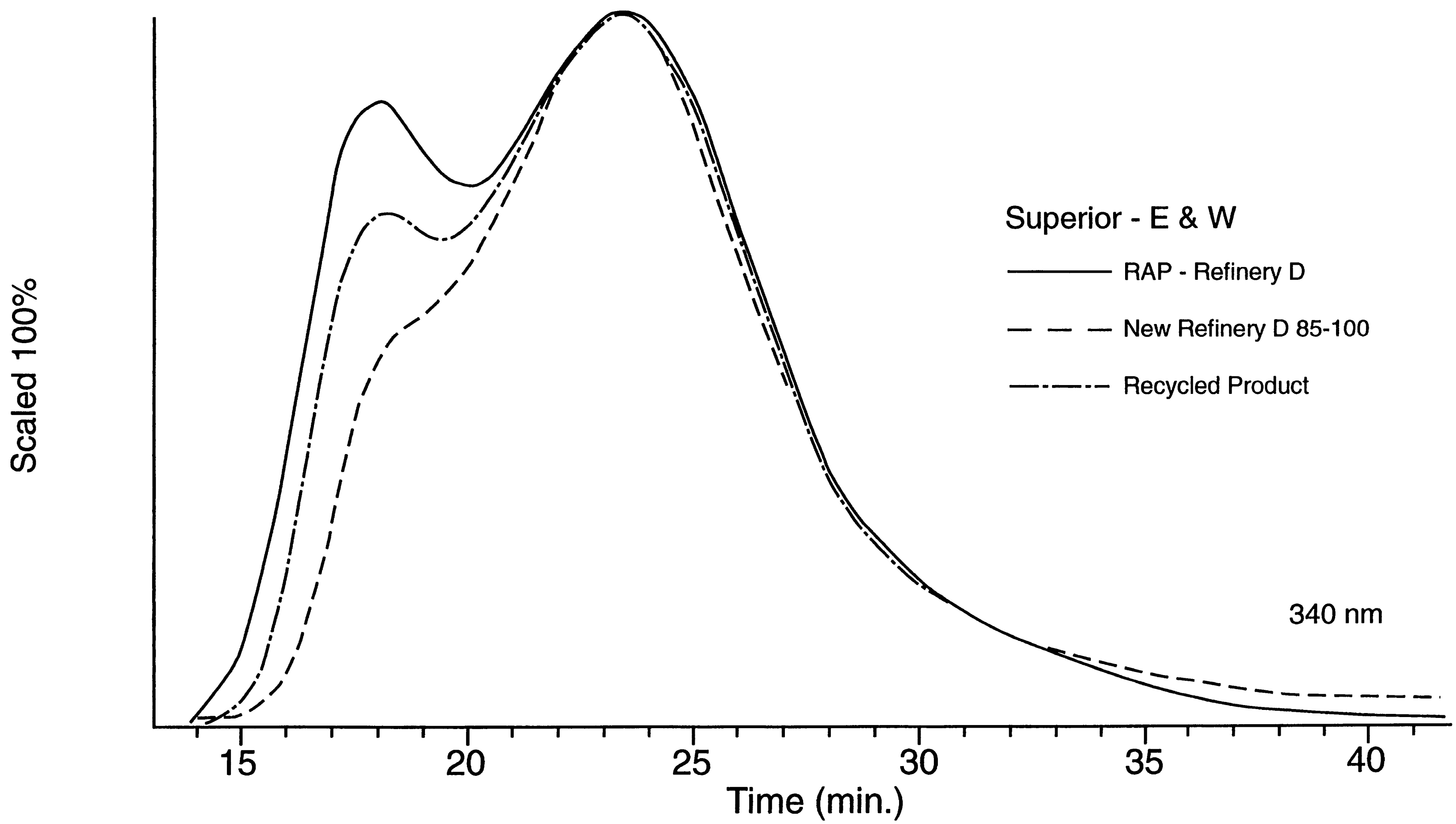


Figure 15. HP-GPC chromatograms of salvaged, virgin and hot-recycled asphalts, Superior, E & W

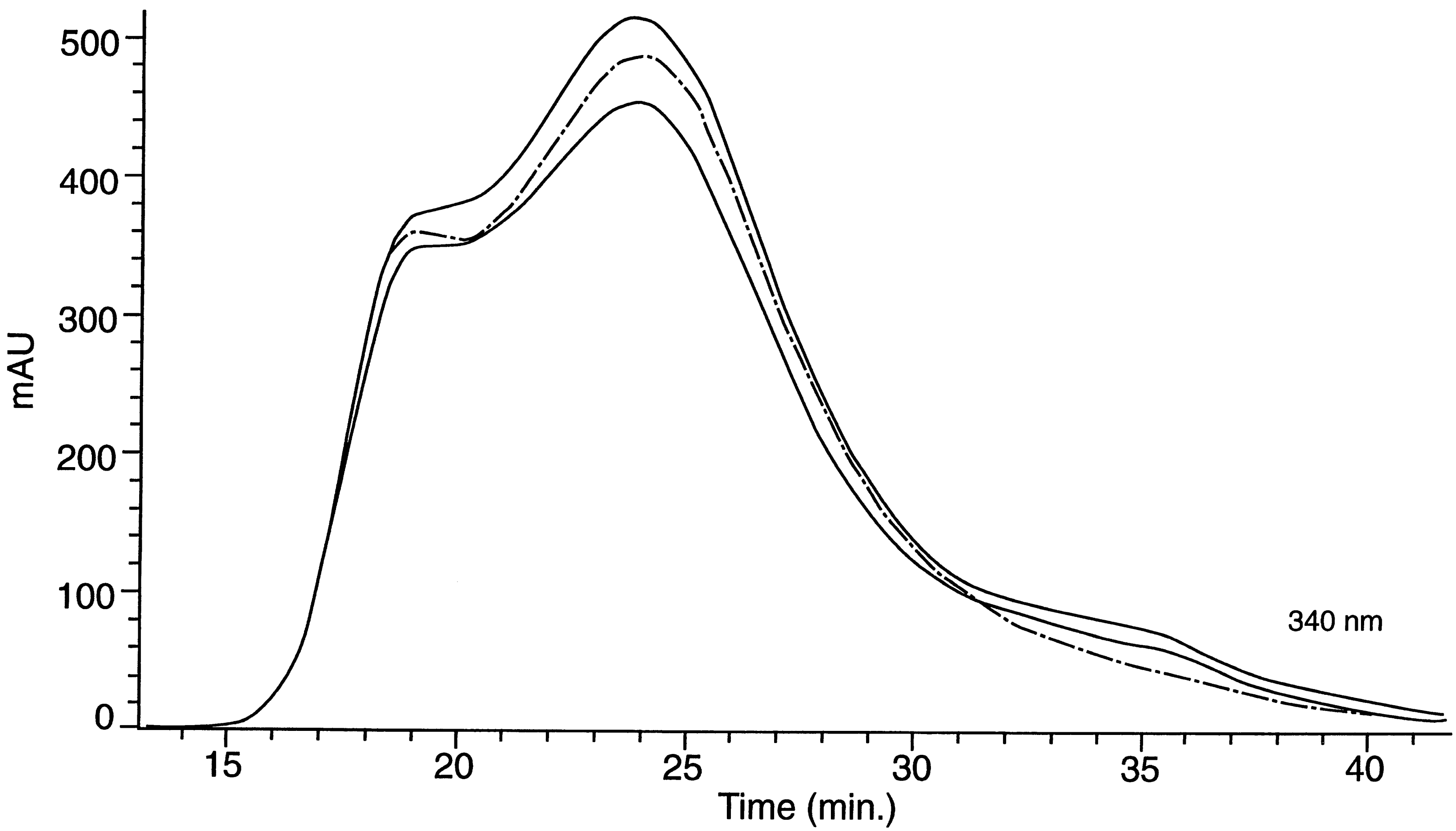


Figure 16. Variations among asphalts recovered from grab samples of Milligan Canyon RAP stockpile

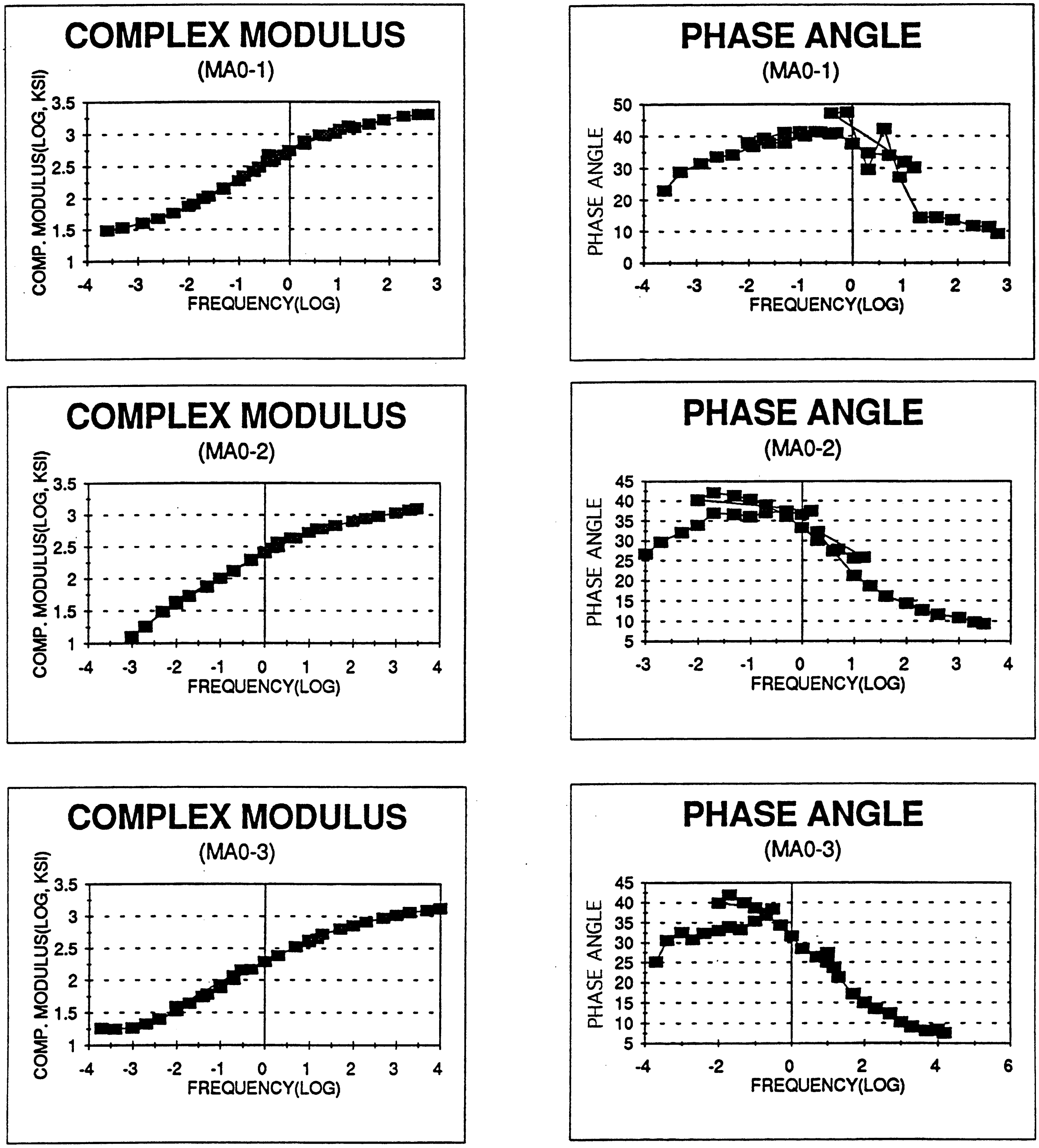


Figure 17. Plots from DMA of Milligan Canyon hot mix simulation, 4.6% AC, unaged.

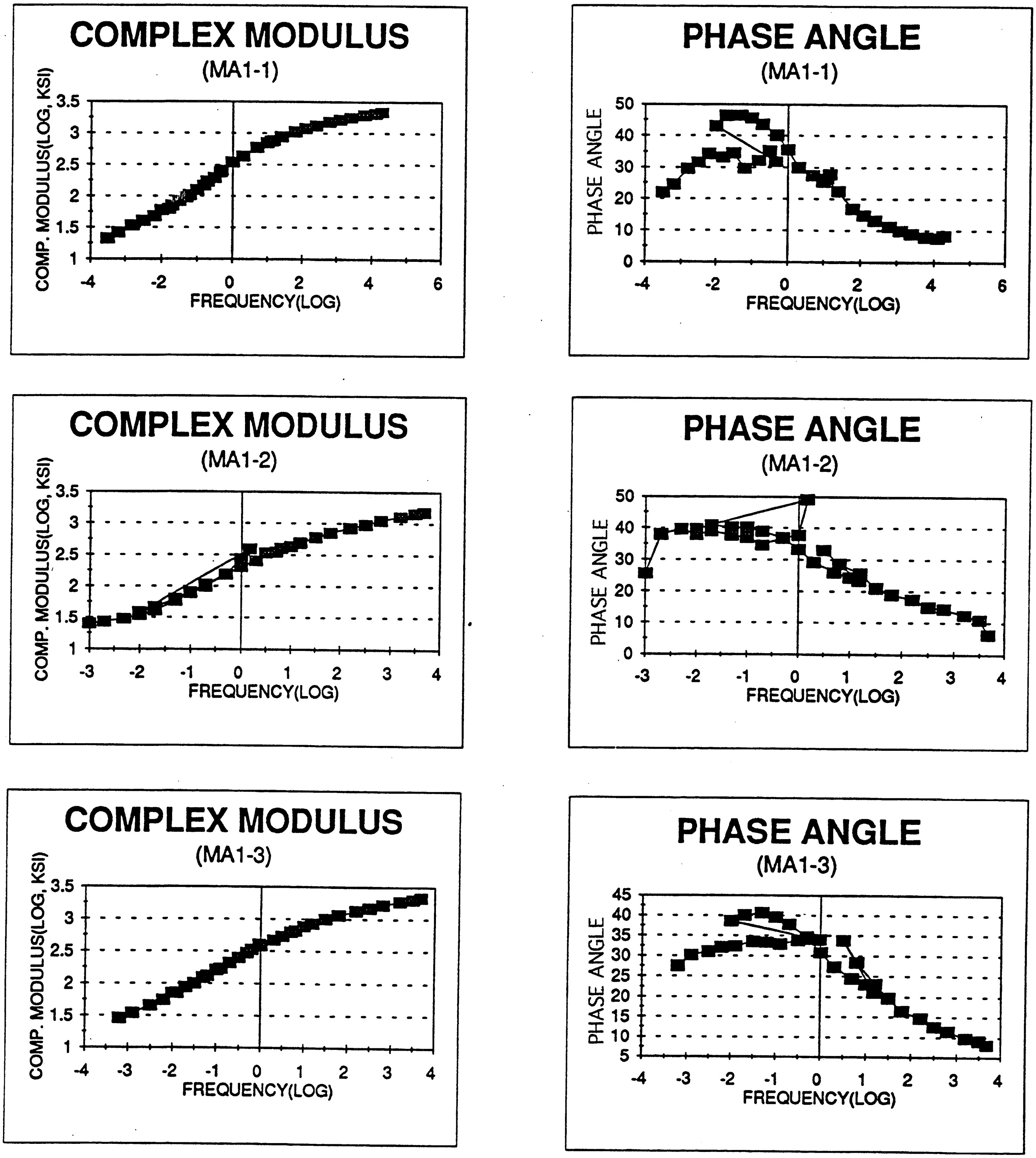


Figure 18. Plots from DMA of Milligan Canyon hot mix simulation, 4.6% AC, aged.

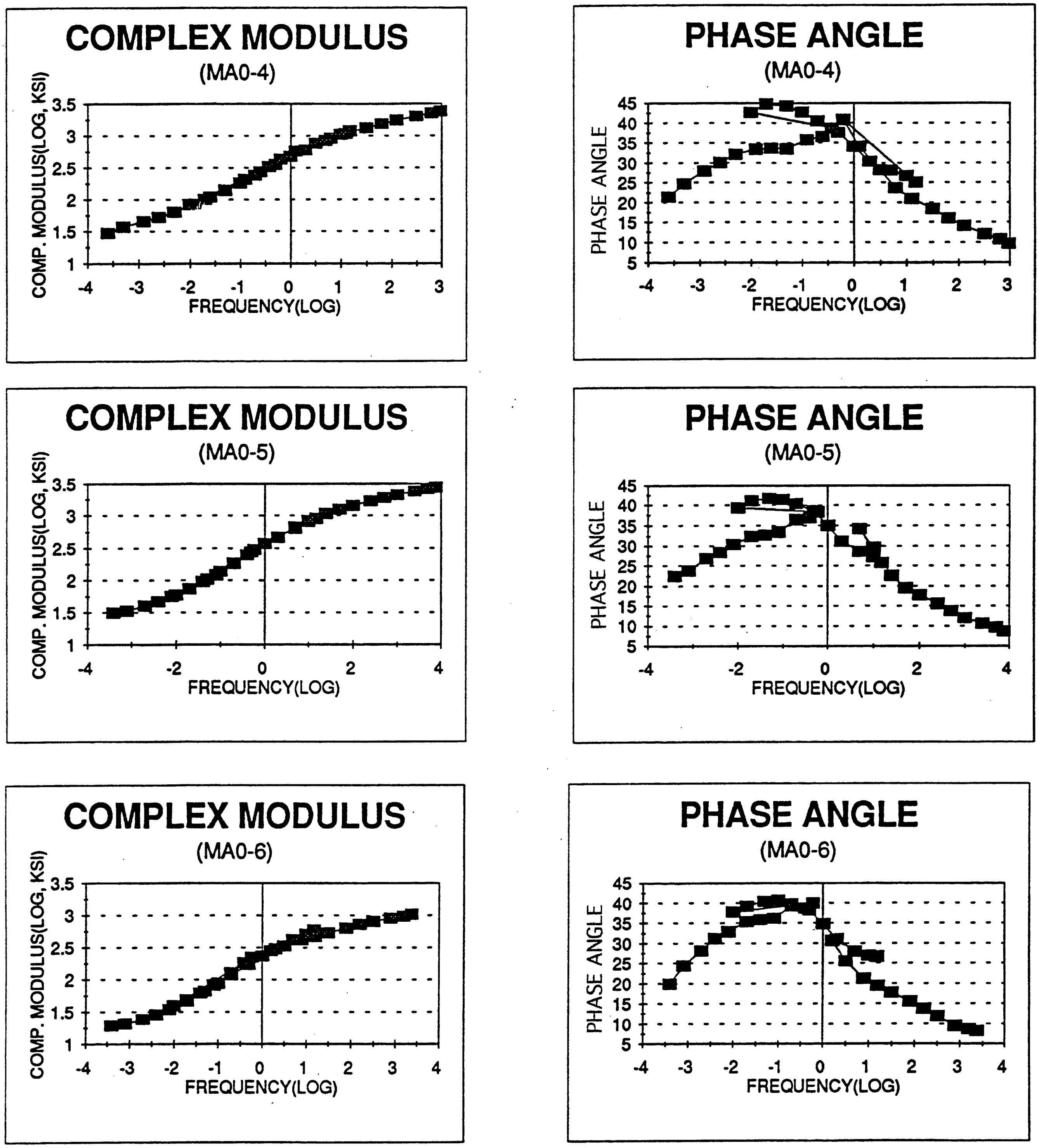
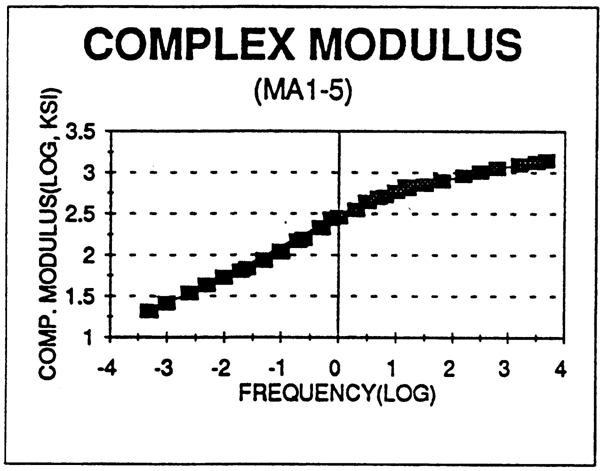
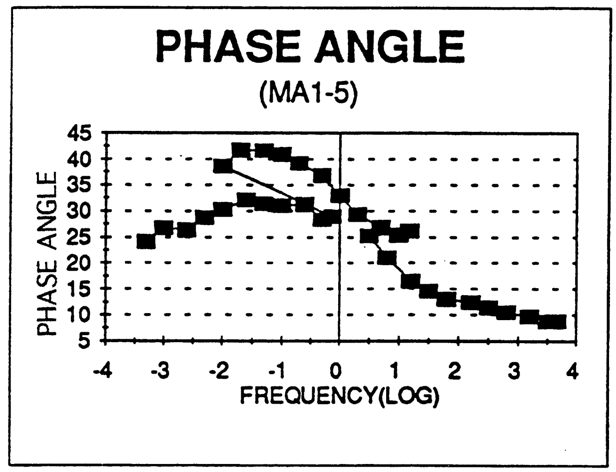
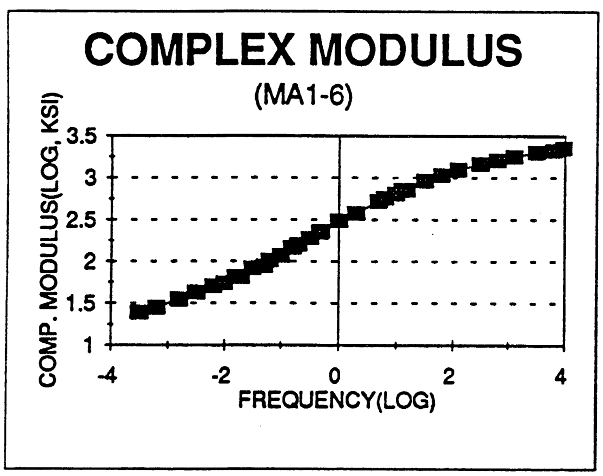


Figure 19. Plots from DMA of Milligan Canyon hot mix simulation, 5.6% AC, unaged.







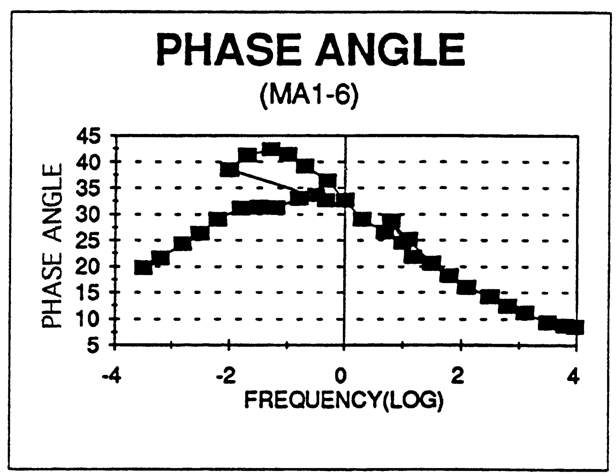


Figure 20. Plots from DMA of Milligan Canyon hot mix simulation, 5.6% AC, aged.

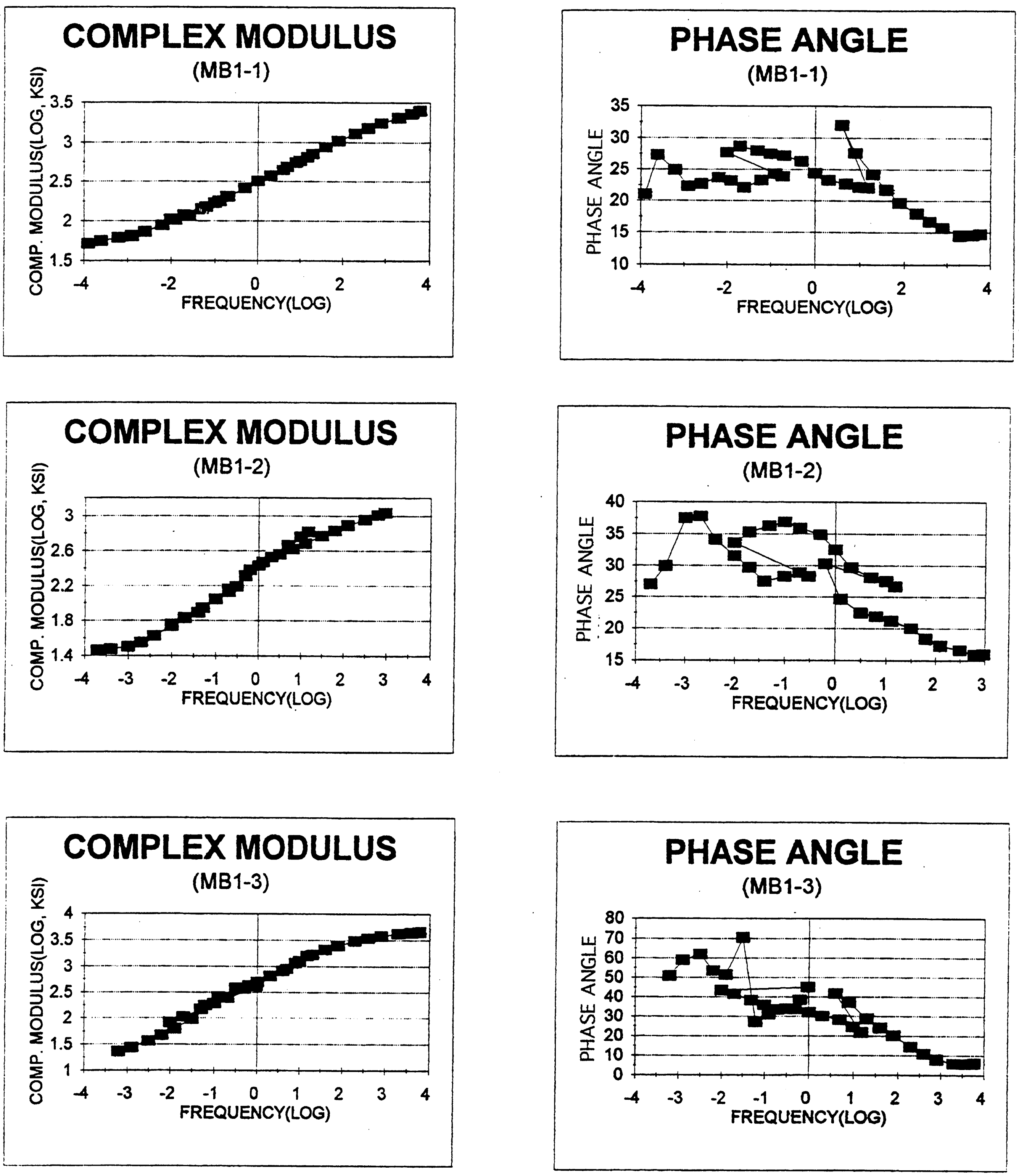


Figure 21. Plots from DMA of Milligan Canyon cold mix simulation with CRS-2P.

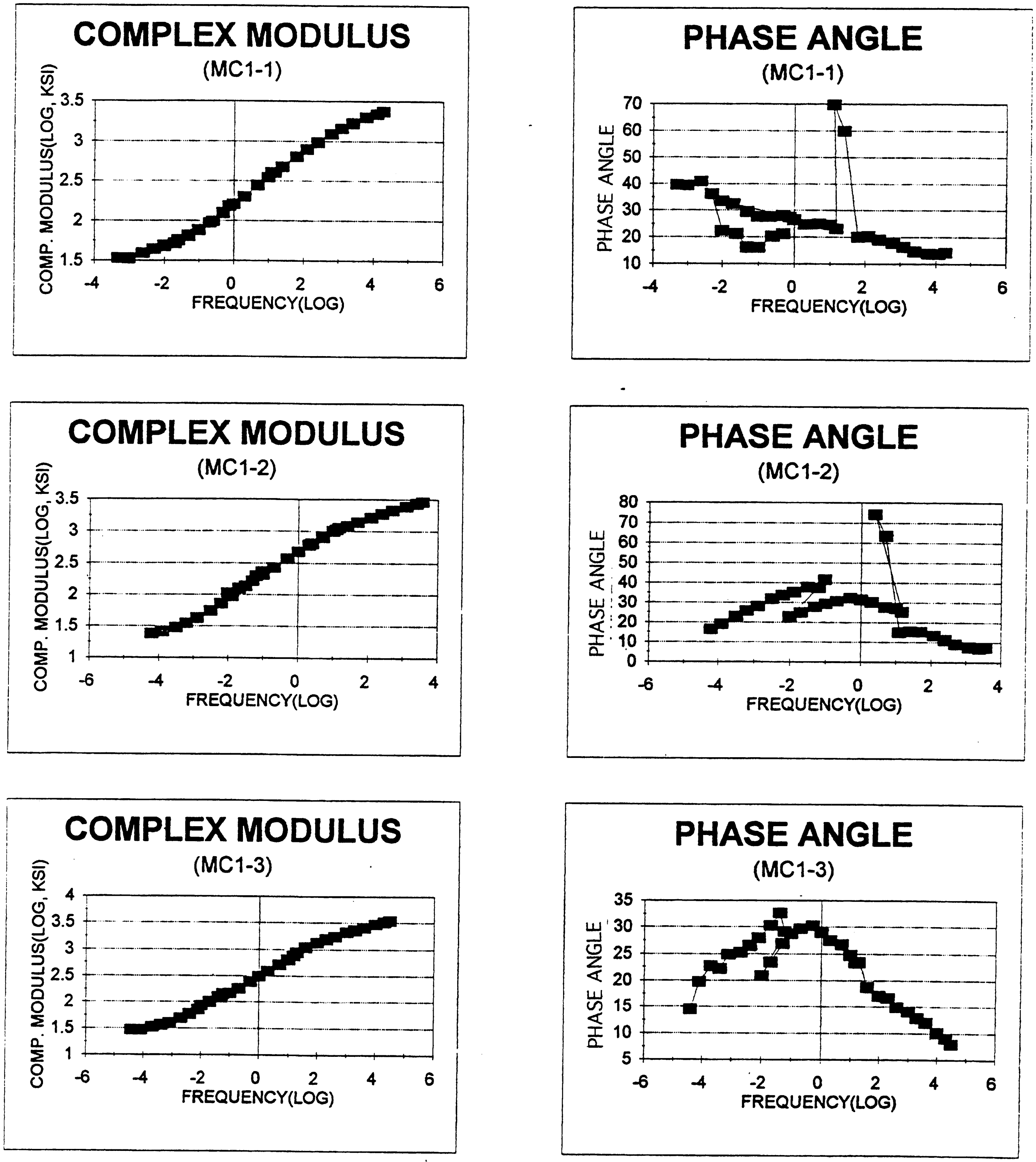
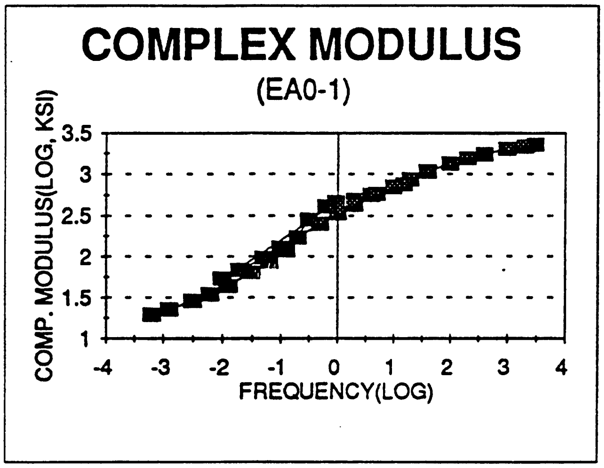
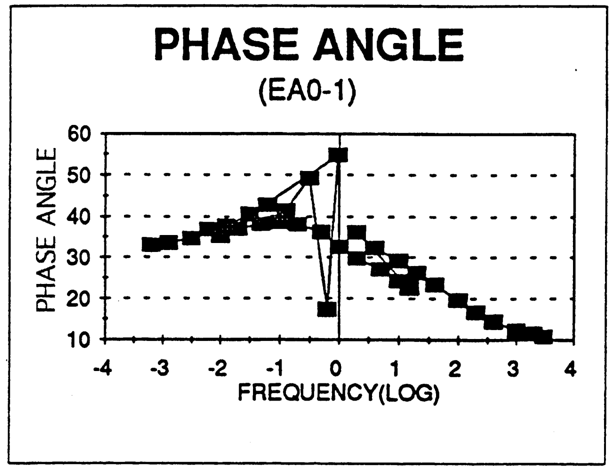
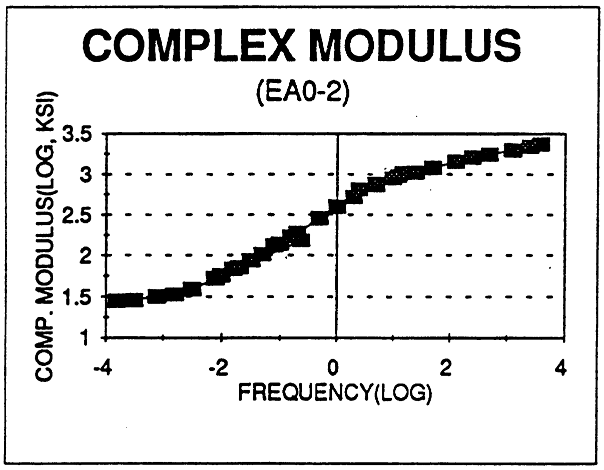
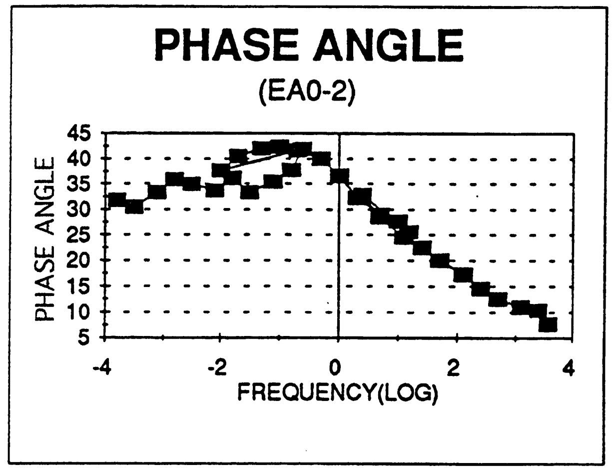


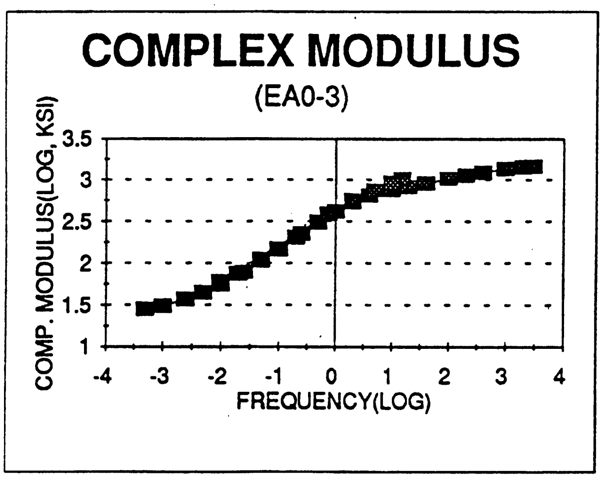
Figure 22. Plots from DMA of Milligan Canyon cold mix simulation with CRS-2P and Recycling Agent II.











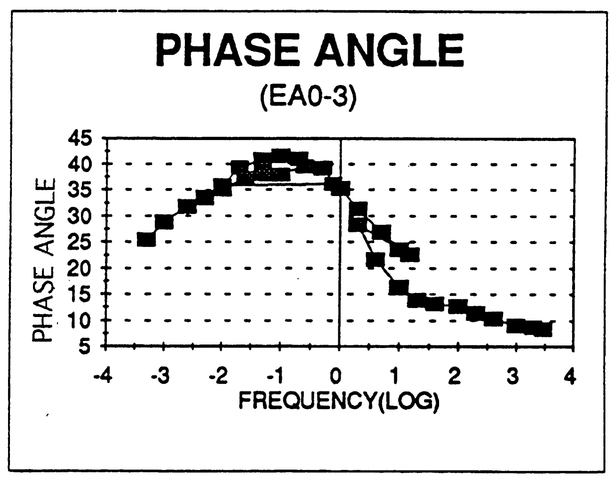


Figure 23. Plots from DMA of Elmo hot mix simulation, unaged.

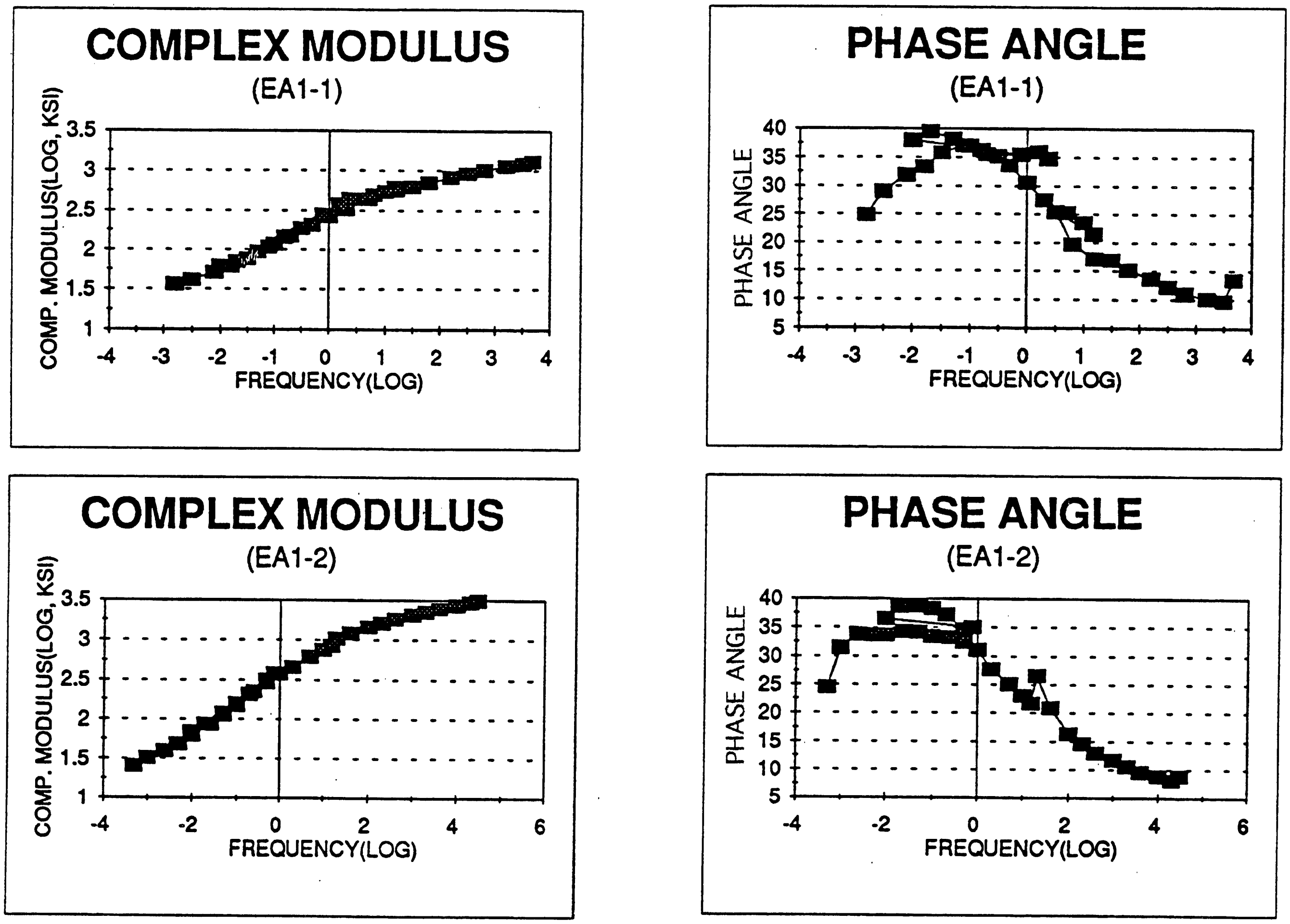


Figure 24. Plots from DMA of Elmo hot mix simulation, aged 149ºC, 4 hr.

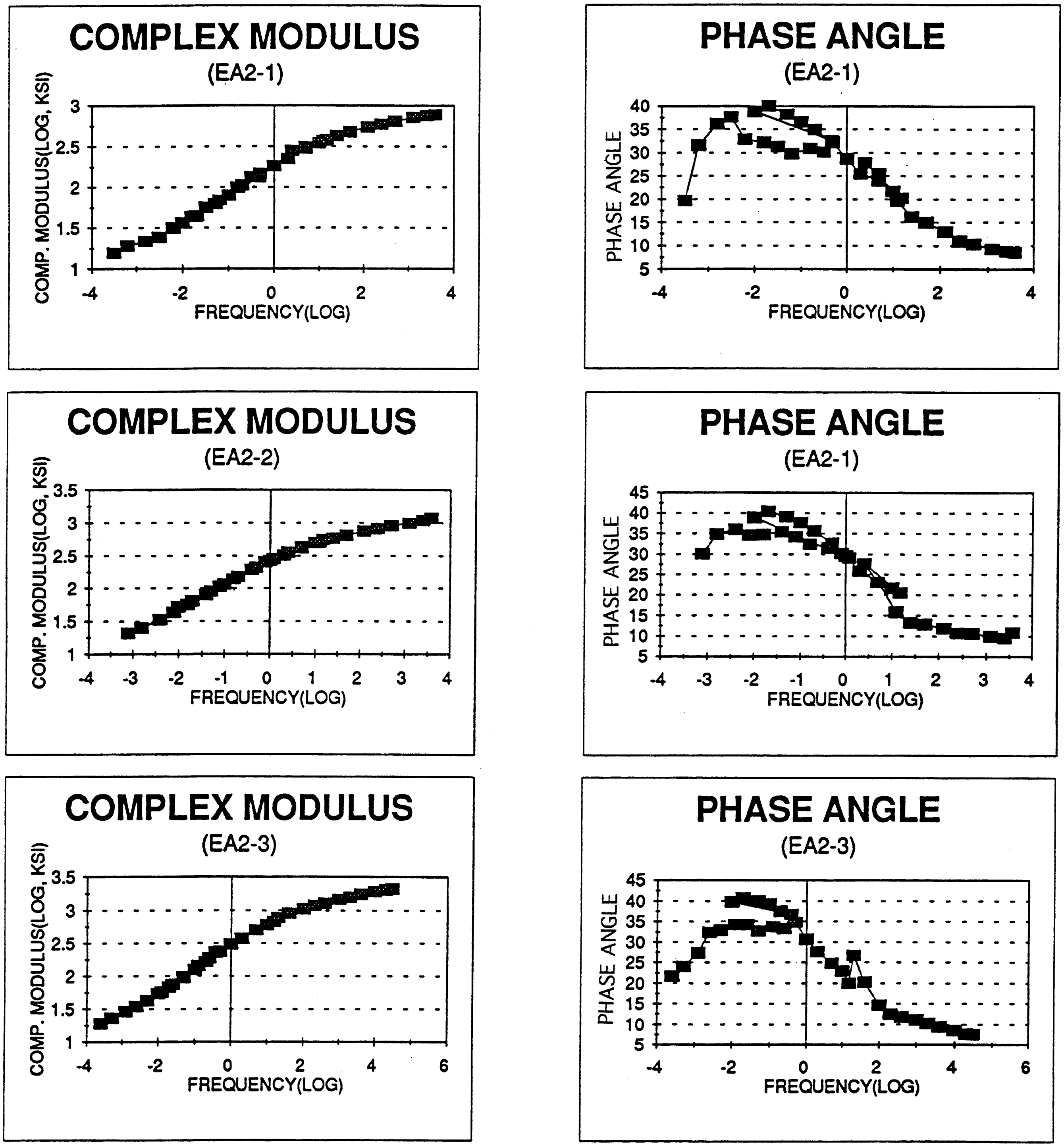


Figure 25. Plots from DMA of Elmo hot mix simulation, aged 135^{o}C, 4 hr.

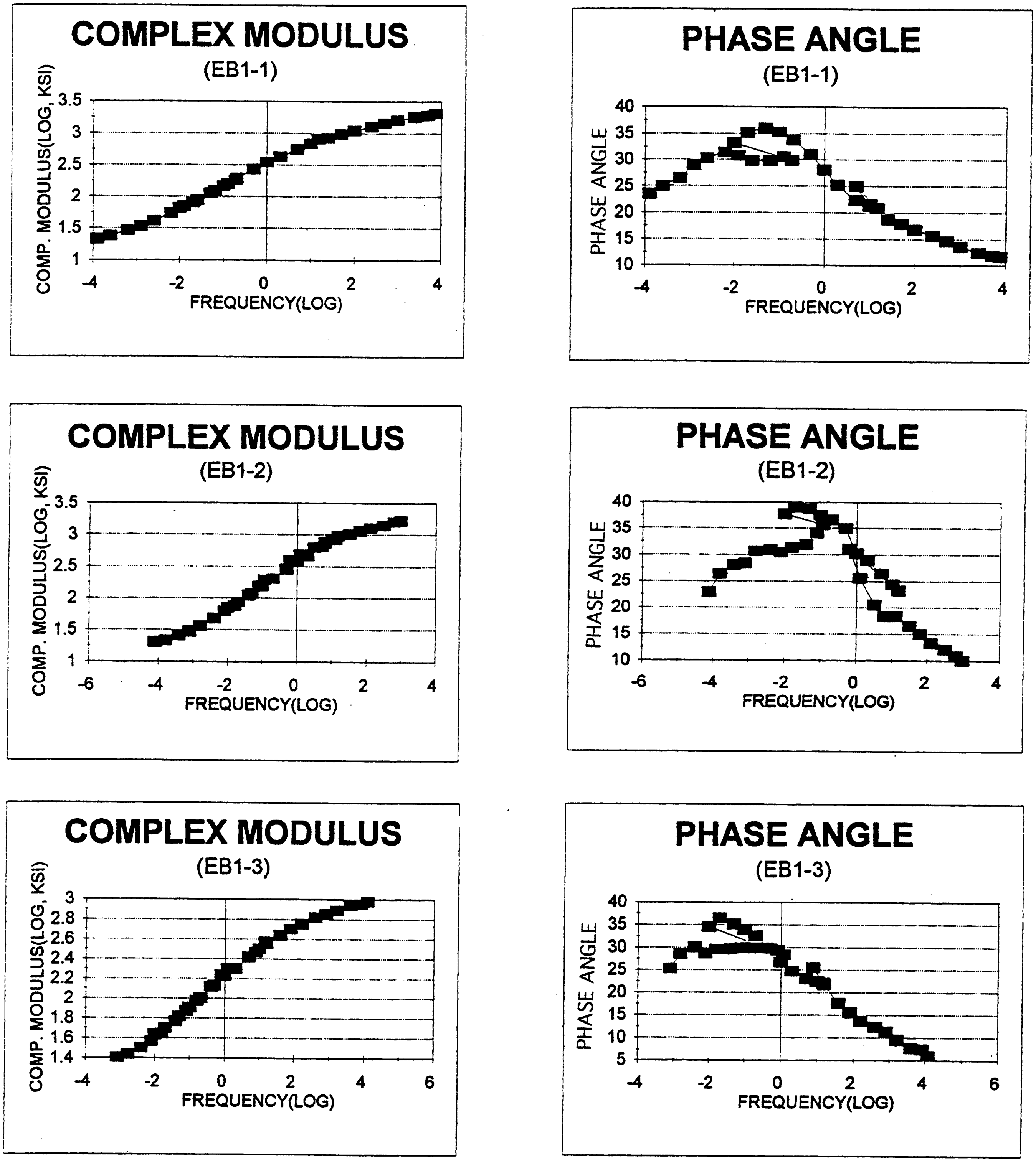


Figure 26. Plots from DMA of Elmo cold mix simulation with CRS-2.

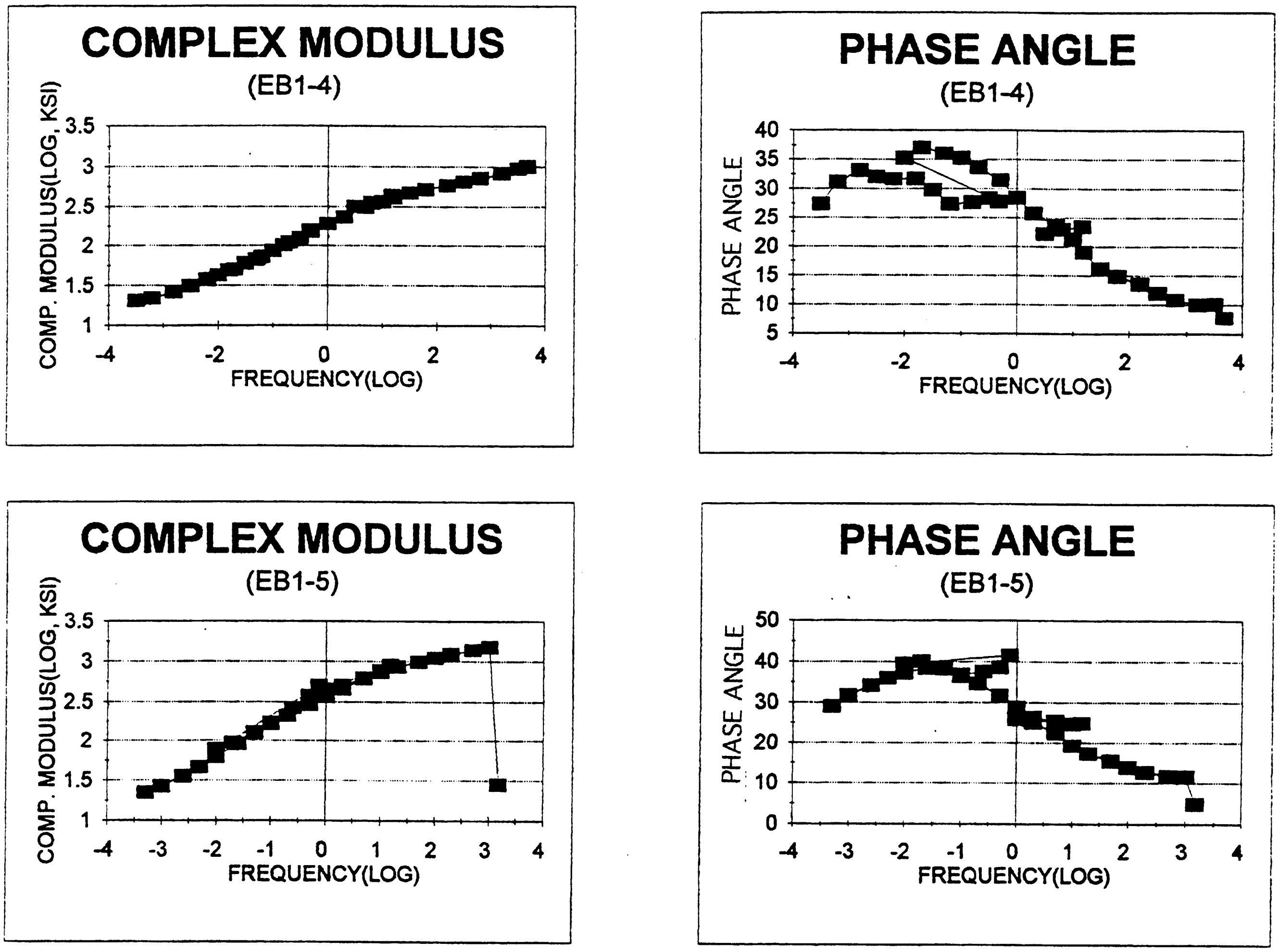


Figure 27. Plots from DMA of Elmo cold mix simulation with CRS-2P.

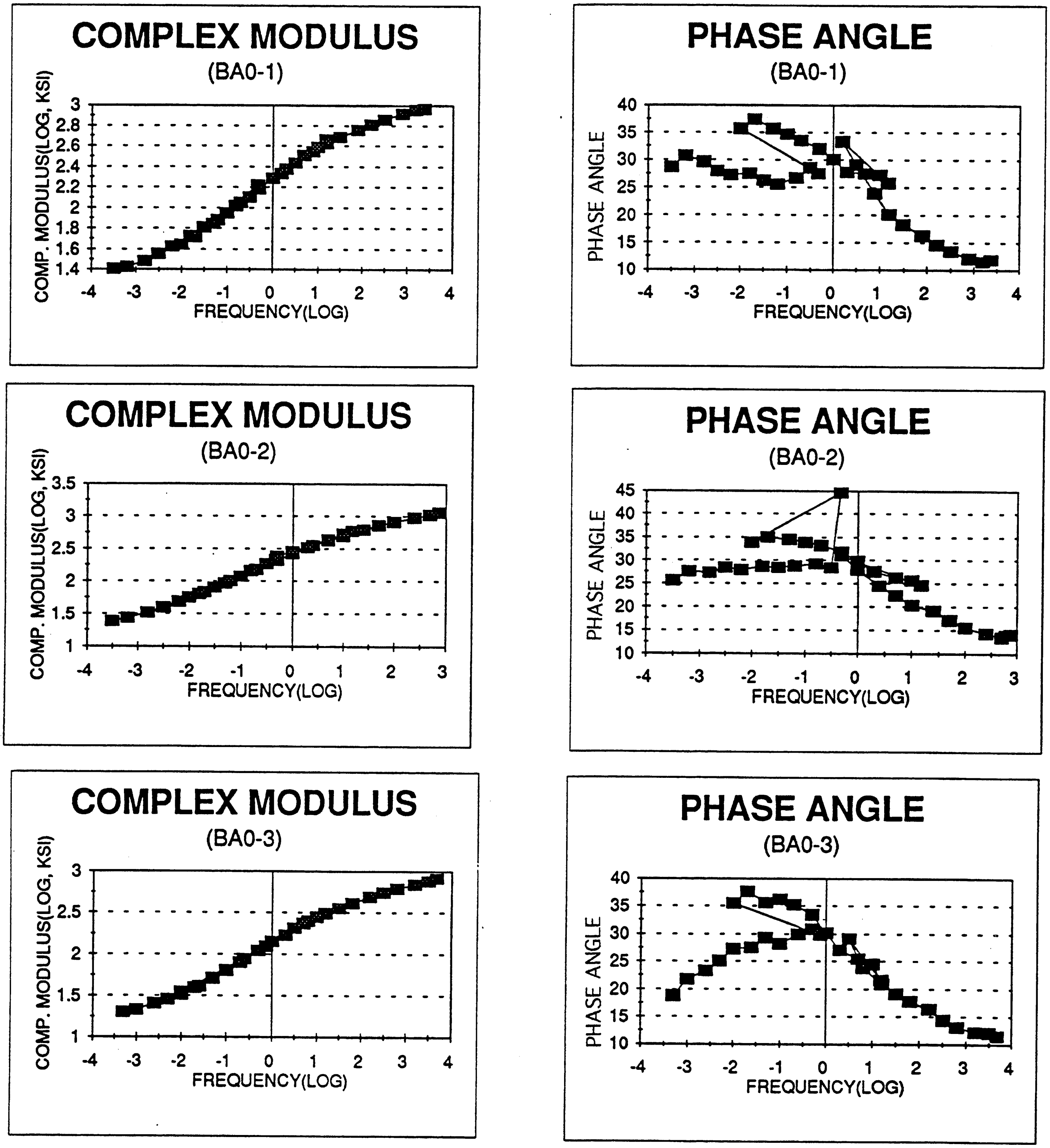
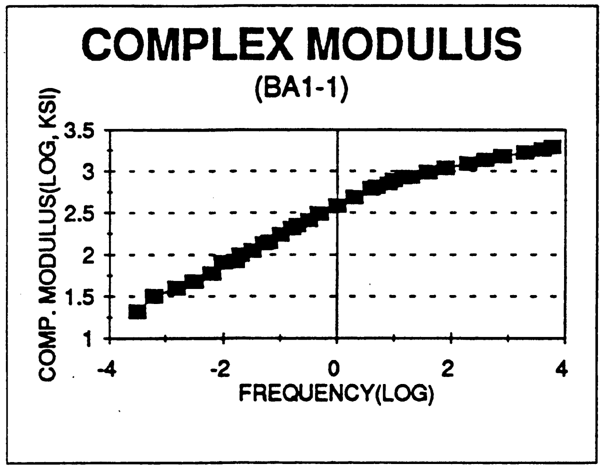
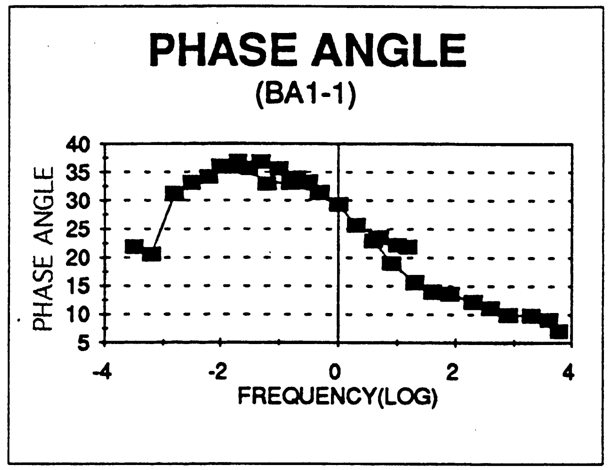
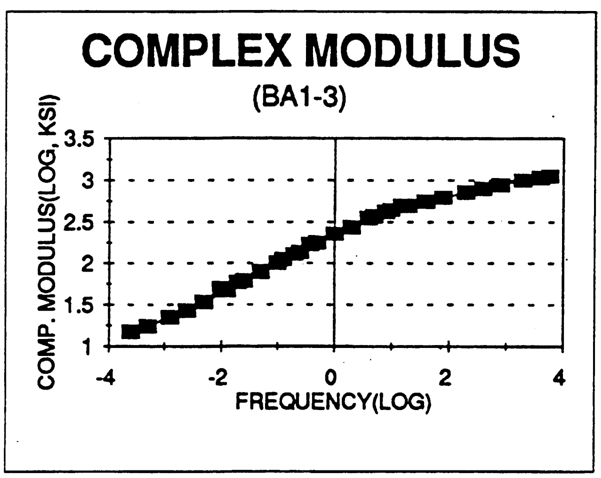


Figure 28. Plots from DMA of Bowman hot mix simulation, unaged.







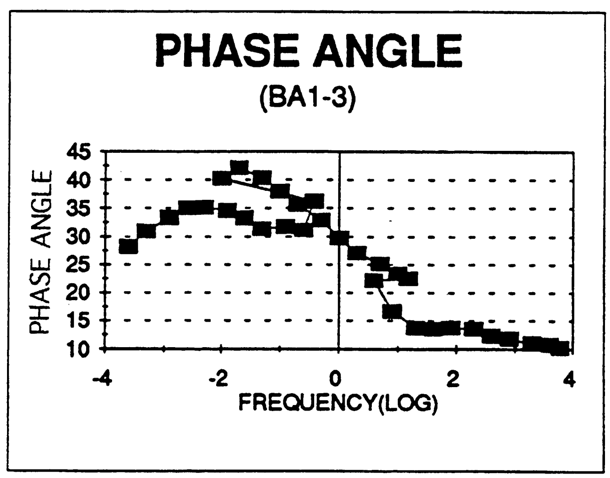


Figure 29. Plots from DMA of Bowman hot mix simulation, aged.

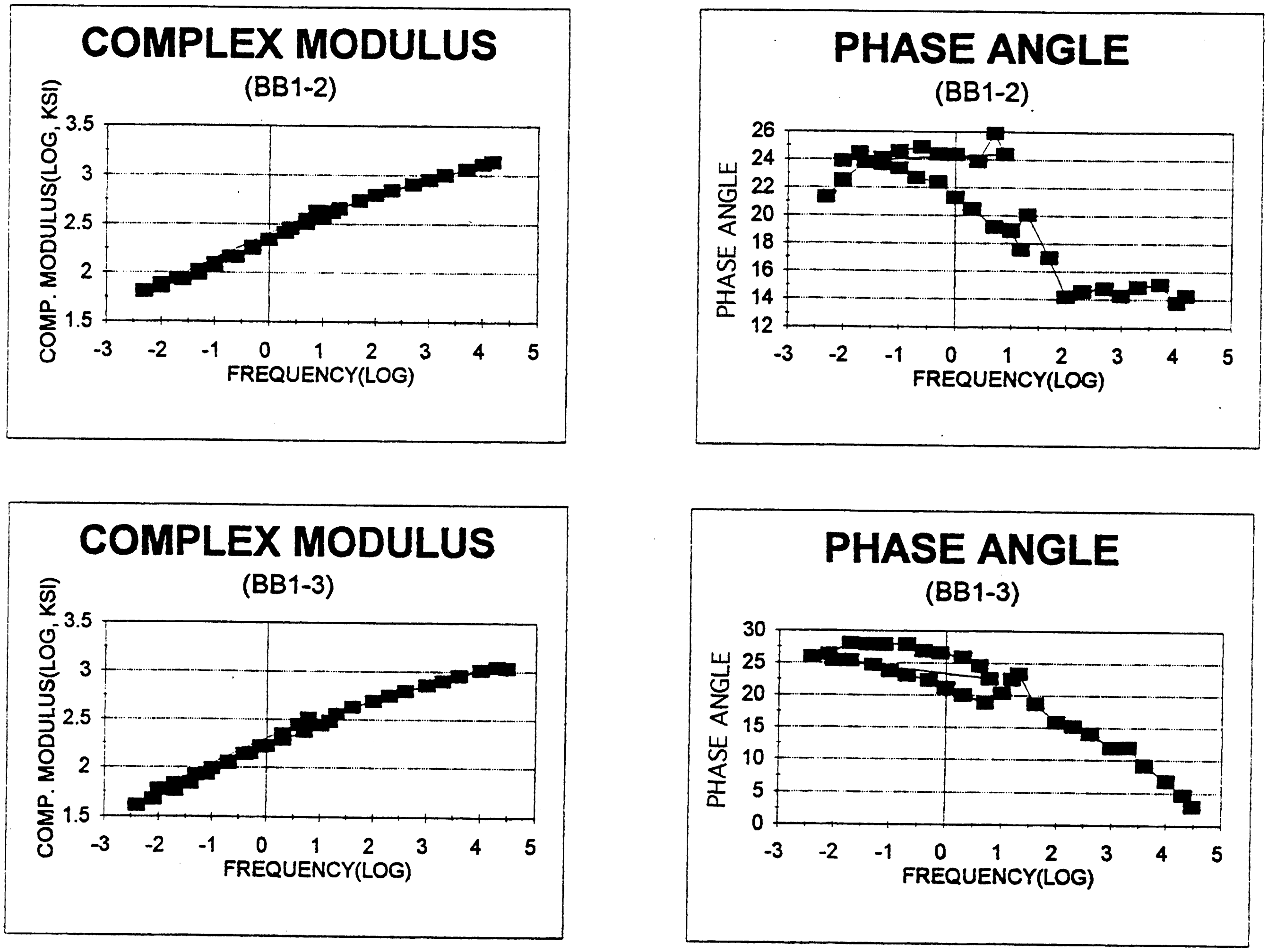


Figure 30. Plots from DMA of Bowman cold mix simulation with CRS-2P.

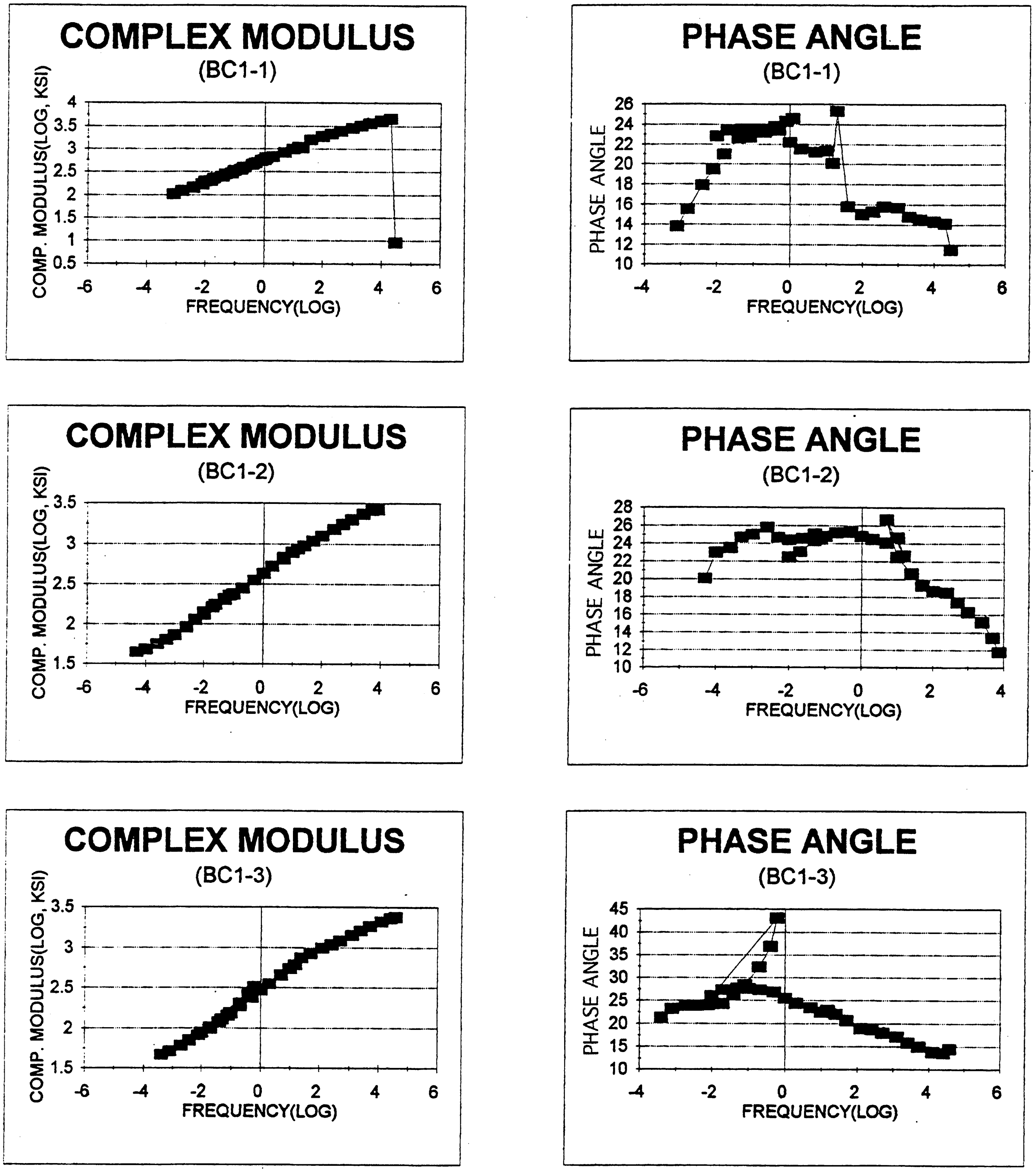


Figure 31. Plots from DMA of Bowman cold mix simulation with Recycling Agent II and CRS-2P.

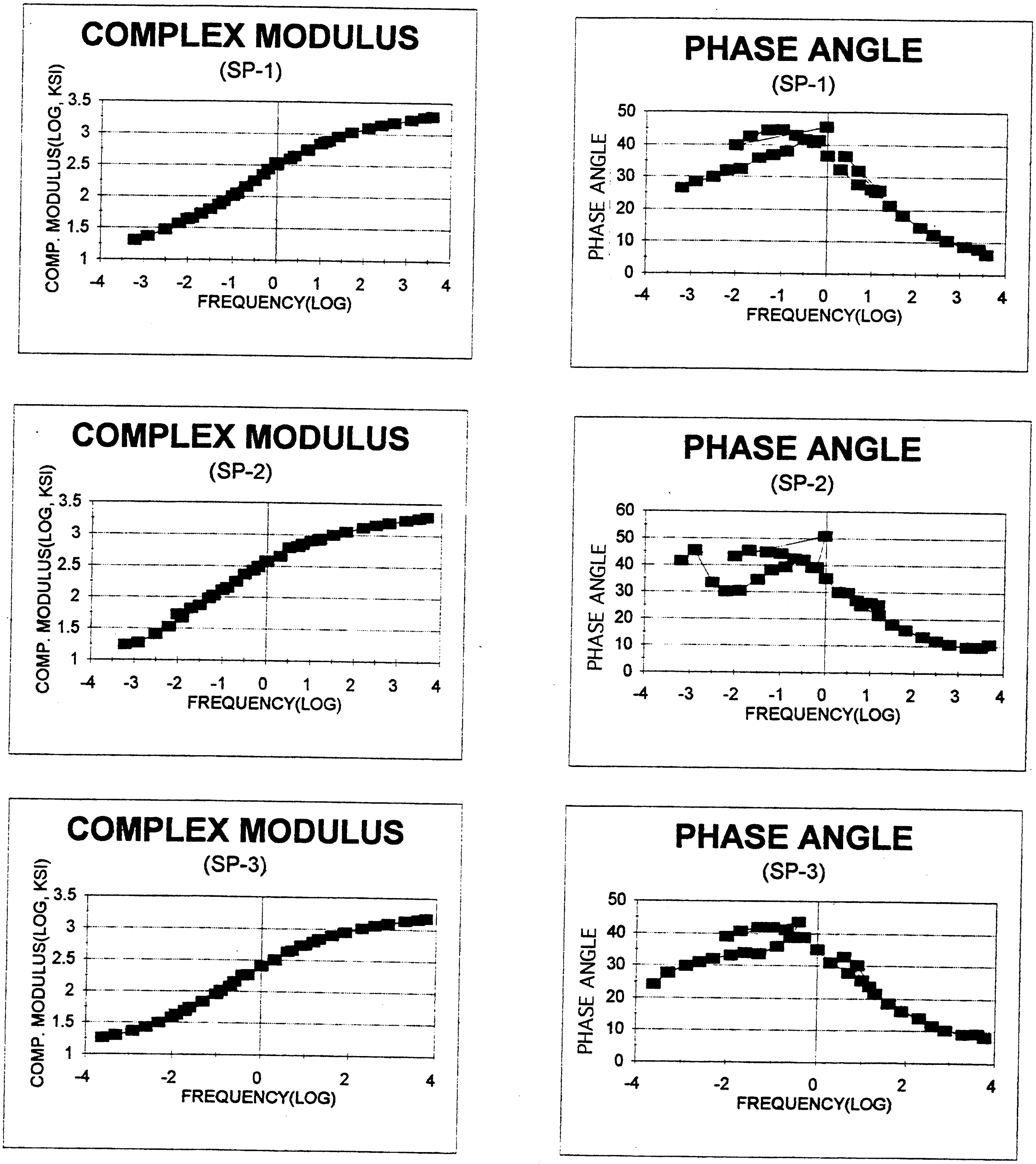


Figure 32. Plots from DMA of typical asphalt mixes with new materials.

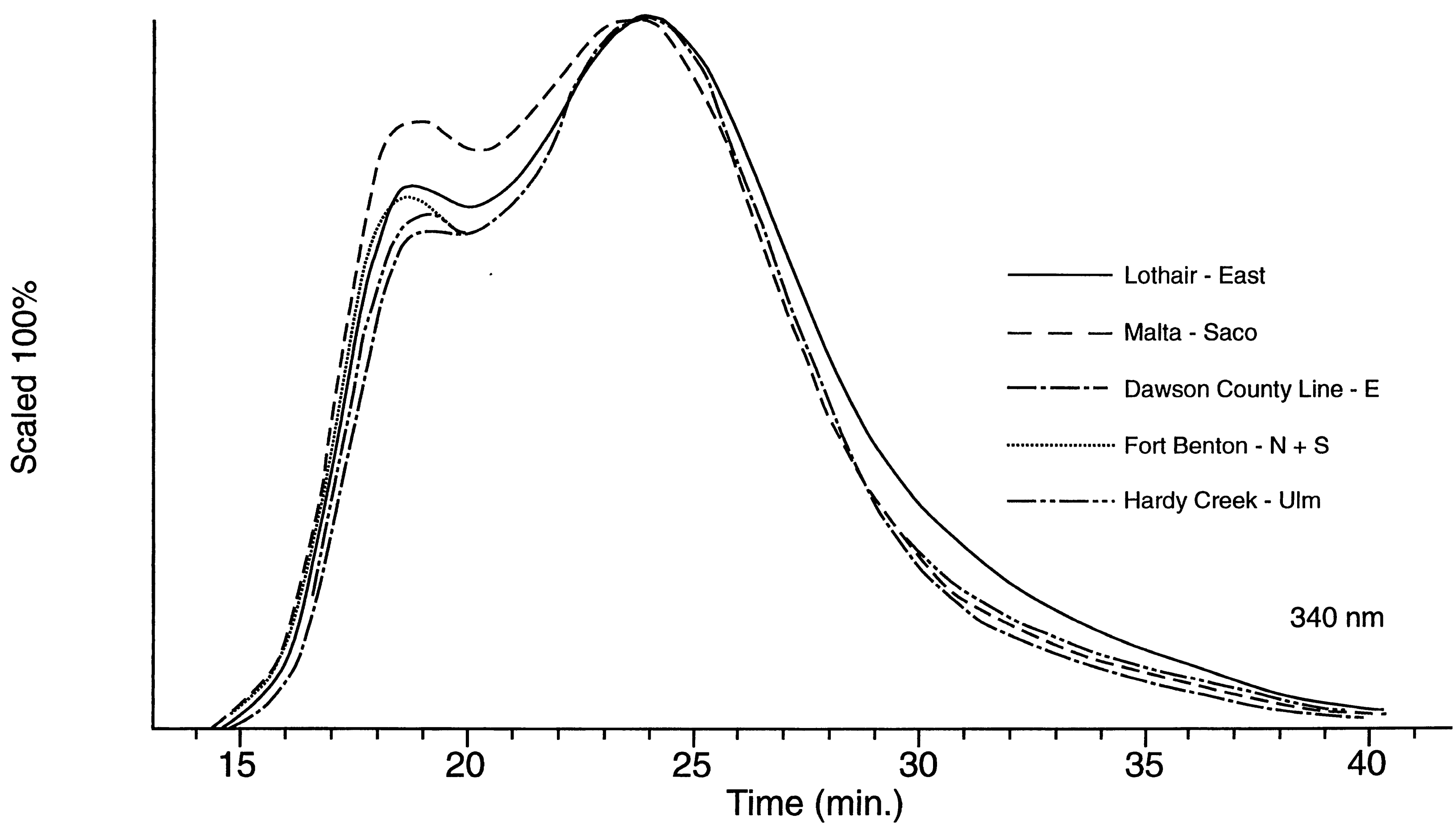


Figure 33. HP-GPC chromatograms of asphalts recovered from potential recycling sites.

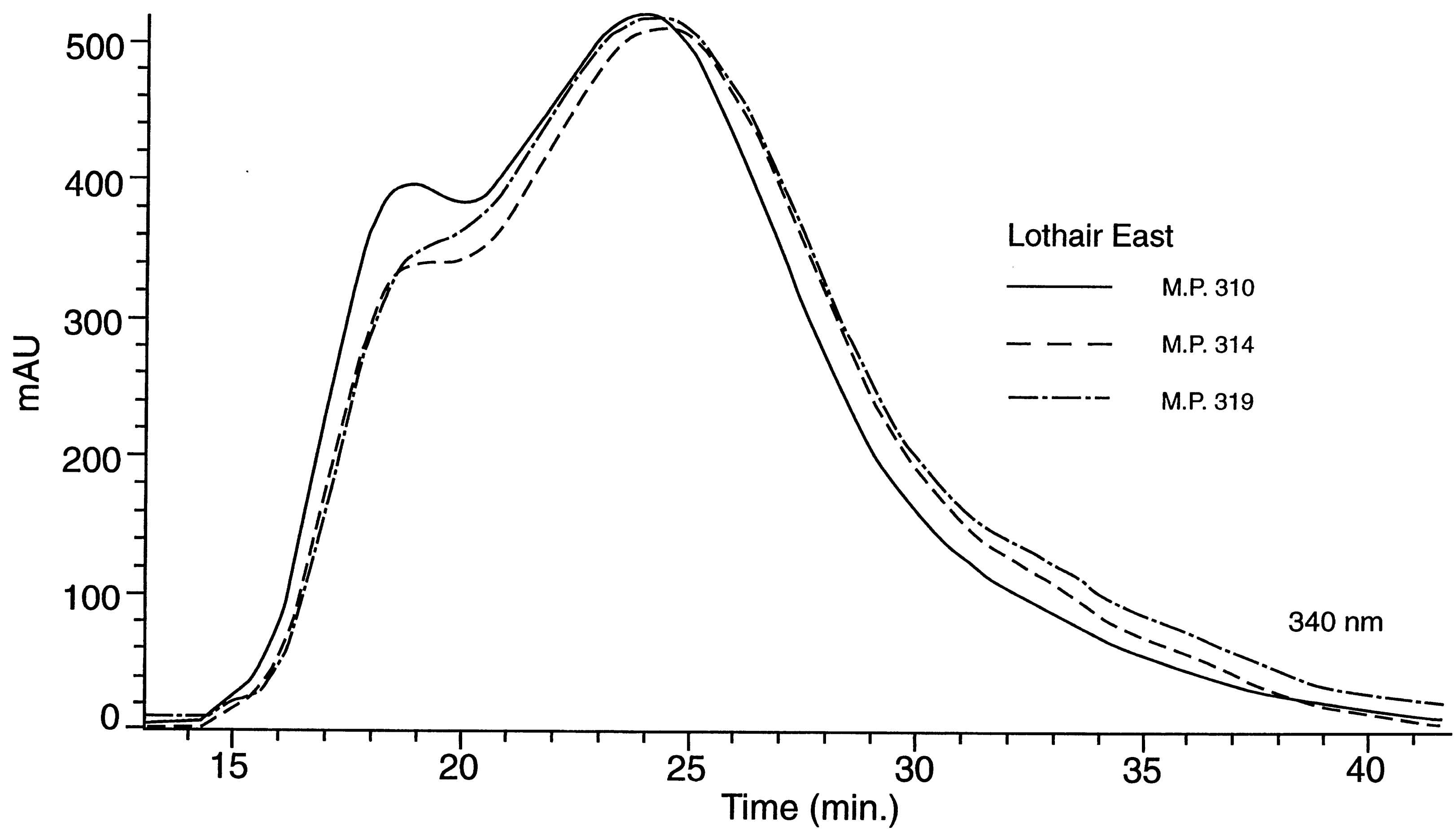


Figure 34. Variations among asphalts extracted from Lothair-E

APPENDIX A

HP-GPC ANALYSIS OF ASPHALT SAMPLES

The HP-GPC technique used in this project utilized the following instrumentation:

· a Waters 6000A series chromatography pump capable of delivering solvent at a rate of 0.1 to 10.0 mls per minute;

· an in-line flow rate meter by Phase Sep capable of measuring flows of 0.1 to 10.0 mls per minute within 1% accuracy, (Phase Sep, Hauppauge, NY);

· a Waters model 6K injector fitted with an appropriate sample loop;

· a diode array detector (DAD) by Hewlett-Packard capable of simultaneous detection of and eight wavelengths from 200 to 600 nm, (Hewlett Packard 1040A HPLC Detection System);

· a 9000 Series 300 Hewlett-Packard computer with HP79988A HPLC Chemstation software, Rev. 5.1, for data acquisition, storage, retrieval and manipulation, plus hard copy output devices;

· a Jordi GPC-GEL 10^3 angstrom, 10 mm ID x 50 cm column (crosslinked styrene-divinyl benzene) (Jordi Assoc. Inc., Bellingham, MA). An in-line, precolumn filter was also used;

· a closed water-circulation system to maintain a constant column temperature of 24^0 C.;

· a solvent reservoir with dry nitrogen or helium purge.

System operating parameters include a mobile phase flow rate for sample and standard analyses of 0.9 ml per minute. The column temperature was maintained at 24^0 C +/- 1^0 C. Seven wavelengths were selected for detection by the DAD: 230, 254, 280, 340, 380, 410 and 440 nm, all with a 4 nm bandwidth. The sampling interval was 3520 milliseconds with a peakwidth setting of 0.5 minutes. Samples required elution times of about 35 minutes

APPENDIX B

PREPARATION OF DMA TEST SPECIMENS

a) Hot, in-place recycling

Compacted specimens were prepared with lightly coated virgin aggregates and RAP from three different pavements (Milligan, Elmo and Bowman). Two aging times (0 hours and 45 minutes) were used for the Milligan and Bowman samples; three aging times (0 hours, 45 minutes and 4 hours) were used for the Elmo samples. Each specimen was left for 48 hours at 25°C before extruding the sample.

The procedure details are:

1) Estimate new asphalt content, virgin aggregate and amount of RAP based on the design specifications for each project.

2) Split RAP and virgin aggregate into batches.

3) Heat virgin aggregate to 163°C for 15 hours prior to hot mixing.

4) Cover RAP with aluminum foil and heat to 116°C for 2 hours prior to hot mixing. Break up larger chunks of RAP.

5) Heat new asphalt to 140°C.

6) Place RAP in mixing bowl and mix for 3 minutes to simulate the case in which rejuvenating agent is used.

7) Add new asphalt to virgin aggregate and mix for 2 minutes.

8) Add virgin mix to RAP and mix for 2 minutes.

9) After mixing is complete, place mixture in a pan and heat at 135°C. for the required aging time.

10) Mold the samples to produce approximately 4-inch briquettes:
   a) preheat the mold to 163°C,
   b) compact the samples in the kneading compactor, 150 blows at 500 psi.

11) Apply "leveling-off" load, place specimen in 60°C oven for 4 hours to reduce variability. After curing is complete, let sample cool to room temperature before extruding.

b)Cold recycling using asphalt emulsions

Compacted specimens were prepared with RAP from three sources (Milligan, Elmo and Bowman). The details of the procedure follow.

1) Split RAP into 1700 g batches.

2) Estimate emulsion requirements based on gradation, asphalt content and asphalt softness.

3) Use 0.5% Recycling Agent I when using the recycling agent and adjust the emulsion requirement by subtracting this 0.5% from the estimated amount of emulsion.

4) Calculate the quantity of water required:
% water = % total liquids - % emulsion.

5) Heat 1700 g samples of RAP, the emulsion and the recycling agent (if appropriate) separately to 60°C for 1 hour.

6) Add water to samples and mix thoroughly by hand.

7) If using recycling agent, add to emulsion and mix thoroughly.

8) Add emulsion to premoistened RAP.

9) Place the material into a pan and cure for 1 hour at 60°C to simulate the average time elapsed between the paver laydown and initial compaction during actual construction.

10) Mold the samples to produce approximately 4-inch briquettes by:
a) preheating the mold to 60°C
b) compacting the samples in the kneading compactor, 150 blows at 150 psi.

11) Apply "leveling off" load (1250 psi).

12) Lay the mold on their sides for 48 hours at 25°C.

13) Extrude the briquettes using the compression testing machine.

14) Determine the bulk specific gravity.
15) Conduct diametral resilient modulus test and dynamic mechanical analysis.