CORRELATION OF LOCALLY-BASED PERFORMANCE OF ASPHALTS WITH THEIR PHYSICOCHEMICAL PARAMETERS

PROGRESS REPORT NO. 2
MARCH 1989

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IOWA DOT PROJECT HR-298
ERI PROJECT 1942

Sponsored by the Highway Division of the Iowa Department of Transportation and the Iowa Highway Research Board

ENGINEERING RESEARCH INSTITUTE

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I. INTRODUCTION

1.1 Background

Current specifications for asphalt cement contain limits on physical properties based on correlations established in the past with field performance of asphalt pavements. Recently, however, concerns have arisen that although current asphalts in use meet these specifications, they are not consistently providing the long service life once achieved.

There are a number of logically possible explanations of this situation:

(1) A considerable concern is associated with the recent world crude oil supply and the economic climate after the 1973 oil embargo which may have affected the properties of asphalt of certain origin (Hodgson, 1984). Blending several crudes, as routinely practiced in refineries to produce asphalts meeting current specifications, may have upset certain delicate balances of compatibility between various asphaltic constituents, which may manifest itself in their long-term field performance but not in original physical properties specified in the specifications (Goodrich et al., 1985; and Petersen, 1984).

(2) The increased volume and loads of traffic on highways, which have occurred over the decades, may have shortened the life span of pavements, indicating the necessity of revising specification limits and/or imposing new provisions to maintain desired durability.

(3) Inadequate mixture design, particularly poor gradation of aggregates, changing construction practices and improper use of additives may also be responsible for early deterioration of asphalt pavements (Anderson and Dukatz, 1985; and Hodgson, 1984).

(4) Specifications based only on physical properties of asphalts do not guarantee adequate performance.

While the performance of the asphalt pavements could be improved by judicious application of improved mix design techniques, more rational thickness design procedures, better construction methods and quality control measures, selection of asphalts based on performance-related properties, tests, and specifications is the key to durable asphalt pavements.

Highway Research Project HR-298 was approved by the Iowa Highway Research Board on December 2, 1986 to study the relationships between the performance of locally available asphalts and their physicochemical properties under Iowa conditions with the ultimate objective of development of locally and performance-based asphalt specifications for durable pavements. Funding for Task 1 (year 1) of the three-year study was authorized in January 1987. A Task 1 Report (Lee and Enustun, 1988) describing work performed and findings resulted during the first year of the study was submitted in January 1988. The report and request for year 2 funding was approved by the Iowa Highway Research Board on February 26, 1988. This report describes work accomplished during the second year of the study.

1.2 Objectives

The objective of this study was to establish locally-based quality and performance criteria for asphalts, and ultimately to develop performance-related specifications based on simple phyiscochemical methods. In addition to physical tests, three of the most promising chemical methods (high performance liquid chromatography or HPLC, thermal analysis or TA and X-ray diffraction or XRD) were selected to analyze samples of:

(a) Virgin asphalts and their residues from thin film oven tests and laboratory accelerated aging tests,

(b) Asphalts extracted from selected field projects including plant mixes, core samples, laboratory mixes prepared using the virgin asphalts and project aggregates, both before and after they are artifically aged in the laboratory, and

(c) Asphalts extracted from pavements with known performance records.

The results obtained will be analyzed to find the fundamental asphalt physicochemical parameters (such as viscosity, molecular size, micelle size, transition temperatures, temperature susceptibility, resistance to oxidative hardening, function groups, etc.) which directly affect the field performance in Iowa.

On the basis of the laboratory-field-performance correlations, we expect to formulate specifications and establish testing procedures which can be performed in the transportation materials laboratories of the Iowa DOT and ISU.

1.3 Program of Study

The ultimate objective of this study is to establish locally-based quality and performance criteria as a basis for asphalt specifications, in other words, the development of performance-based specifications for the state of Iowa.

This research will be carried out in six tasks completed in three years. The specific tasks to be performed were presented in the research proposal and are shown in Figure 1.

2. EXPERIMENTAL

2.1 Materials

To accelerate the study and to gain an additional year of field performance record, it was decided to proceed with Tasks 2 and 3 at the same time. Ten hot mix field pavement projects were selected by the engineers of the Iowa Department of Transportation to represent a range of asphalt source, asphalt grade and type of projects in Iowa. The selected projects included four AC-5s, two AC-10s and four AC-20s. The projects consisted of two Interstate projects, three primary and five secondary highways, three of which were placed as surface, two as binder and five as base courses. A summary of these projects is given in Table 1. The project locations are shown in Figure 2.

From each project, one gallon of original asphalt cement, 30 to 50 lbs of virgin aggregates and 30 to 50 lbs of plant mix were collected. In addition, 2 to 3 core samples were taken after compaction. These samples were obtained between August and November 1988.

2.2 Procedures

From each of the 10 sets of field samples, the following asphalt cement samples were derived for physicochemical characterization:

- PAO: Virgin or original asphalt.
- PAR: Thin-film oven test residue following ASTM D1754.
- PO: Laboratory aged asphalt following pressure-oxidation procedure (20 atm of oxygen at 140°F for 46 hrs) developed under HR-124 (Lee, 1968 and 1974). This procedure was developed to simulate field in-service aging under Iowa climatic conditions.
- PM: Asphalt cement extracted and recovered from plant mix.
- PC: Asphalt cement extracted and recovered from core samples.

- LM: Asphalt cement recovered from laboratory prepared hot mix following plant job mix formula using virgin aggregates and asphalt cement from the project.
- L35: Asphalt cement recovered from laboratory mix, compacted by 35-blow Marshall procedure and aged in oven at 140°F for 12 days (Goode and Lufsey, 1965 and Page et al., 1985). This procedure was developed to simulate in-service asphalt aging in pavements of high voids.
- L75: Asphalt cement recovered from laboratory mix, compacted by 75-blow Marshall procedure and aged in oven at 140°F for 12 days. This procedure was designed to simulate in-service asphalt aging in pavements of low void levels.

In the following discussion these asphalt sample codes will be preceded by a project number identified in Table 1.

2.2.1 Rheological properties: Penetration at 5°C (100 g, 5 sec), penetration at 25°C (100 g, 5 sec), penetration at 4°C (200 g, 60 sec), viscosity at 25, 60 and 135°C, and ring-and-ball softening point tests were performed on original (PAO), TFOT aged residue (PAR) and pressure-oxidation aged asphalts (PO), as well as asphalts recovered from plant mixes (PM), core samples (PC) and laboratory mixed (LM), compacted and aged samples at two void levels (L35 and L75). From these data penetration ratio (PR), penetration index (PI), pen-vis number (PVN), viscosity temperature susceptibility (VTS), cracking temperature (CT), critical stiffness and critical stiffness temperature were calculated (The Asphalt Institute, 1981; Button et al., 1983). Based on viscosity data at 25°C, shear index (SI, the slope of log viscosity versus log shear rate plot) and complex flow (c, the slope of log shear stress versus log shear rate plot) were also determined (Lee, 1974).

2.2.2 High performance liquid chromatography (HPLC): HPLC, specifically high pressure gel permeation chromatography (HP-GPC) is a technique by which the molecular size distribution of asphalt is determined by means of gels of selected pore sizes as in sieve analysis. Recent reports from a Montana asphalt quality study using this technique have shown considerable promise and have led the Montana State Department of Highways to institute special provisions based on requirements based on HP-GPC (Jennings et al., 1982, 1985, and 1988). While there were unresolved exceptions, it has been concluded that large molecular size asphaltic constituents contribute to low-temperature cracking of asphalt pavements. Other studies (Zenewitz and Tran, 1987; and Button et al., 1983) have related the amounts of small molecular size fractions to rutting and tender mixtures. Garrick and Wood (1988) reported correlations between asphalt chemical composition by HP-GPC and performance characteristics of asphalts and asphalt mixtures. Edler et al. (1984), in South Africa, found correlations between pavement deformation and bleeding and asphalts of certain molecular profiles as determined by HP-GPC. More recently, Goodrich (1988) found association between asphalts with wide distribution of molecular sizes as determined by HP-GPC, aging, and desirable mix characteristics with respect to low-temperature creep (thermal cracking), flexural fatigue and high-temperature creep (rutting resistance). Work underway at Indiana, Kansas and Georgia Highway Departments (Bishara and Wilkins, 1989; Noureldin and Wood, 1989; and Caylor and Sharp, 1987) have also shown that the HP-GPC technique can be used as a reliable test to relate chemical composition and aging characteristics of asphalts.

A high performance gel permeation chromatography (HP-GPC) system (Waters) was used during this study. The instrumentation and procedure was described earlier (Lee and Enustun, 1988). To better characterize the molecular size distribution of the asphalts, the HP-GPC profiles were analyzed by three different procedures. The normalized chromatographs were divided into three, four and eight slices following Montana State (Jennings, et al., 1980), Iowa State (Lee and Enustun, 1988) and Purdue (Garrick and Wood, 1988) procedures.

2.2.3 Thermal analyses: Thermal analysis techniques have been used extensively by chemists to identify and characterize polymers. Breen and Stephens (1967) and Schmidt (1966) recommended the use of glass transition temperature from thermal analysis data for predicting low-temperature cracking of asphalt pavements and also point out the possibility of using it for predicting cracks due to aging.

The determination of glass transition temperature using the differential scanning calorimetry (DSC) technique was described in the Task 1 Report. In the present study, an improved thermal mechanical analysis (TMA) technique was used.

Basically, the thermomechanical analyzer (TMA) measures changes in mechanical properties of a sample resulting from changes in temperature and elapse of time. A sample in the TMA is compressed or held in tension by a probe assembly. Movement of the probe is detected by a Linear Variable Differential Transformer (LVDT) and recorded on a Thermomechanical Analyzer Programmer. By using interchangeable probes, several measurements can be made including softening point, compression modulus, glass transition, and expansion coefficient.

In this study, a DuPont 943 thermomechanical analyzer was used. The TMA attachment was connected to a DuPont Thermal Analyzer Programmer 1090 by which the TMA unit was controlled. By using expansion probe (contact diameter of 0.1 in.), the glass transition temperatures of 60 asphalt samples were determined.

Asphalt samples mounted for TMA were 3 mm thick and about 5 x 5 mm square. They were prepared as follows: about 5 gram of asphalt sample was placed on aluminum foil resting on a smooth and hard surface. Two 3 mm thick metal plates were placed at both sides of the asphalt sample. The sample was covered by clean aluminum foil which was lubricated with a thin film of glycerin + talcum powder mixture. The sample was then pressed by means of a smooth bottom heavy metal piece until contact is made with both 3 mm thick metal plates. Removing the lubricated aluminum foil, the pressed asphalt was cut in 5 x 5 mm size. TMA samples from very soft asphalts (some of the AC-5 samples) were prepared at a lowered temperature (in refrigerator or freezer). The sample was then inserted in the sample-holder tube. Penetration probe was lowered until it just touched the sample. Liquid nitrogen was poured in a Dewar flask up to 1/3 - 1/2 full. The heating unit was slowly lowered into the Dewar flask. After boiling of the liquid nitrogen slowed down, the heating unit and Dewar flask were attached to the TMA base unit. When the temperature reached -60°C, to ensure the correct contact between the probe and the surface of the asphalt sample, the probe was slightly lowered, and the transducer position was adjusted to give a zero reading at the thermal analyzer control board. When the temperature reached -70°C, the test automatically started. The temperature was kept at -70°C for 10 minutes, and then increased at a rate of 5°C per minute up to 25°C.

2.2.4 Nuclear magnetic resonance (NMR): It has been shown that valuable information can be obtained by ^{13}C and proton NMR studies of asphalts regarding the average chemical functionality, e.g. carbon and hydrogen aromaticity, carbons with attached and non-attached hydrogen, as well as heteroatom (nitrogen and hydrogen functionality, in asphaltenes) for characterization of asphalts (Gerstein, 1983; 1986).

Four samples studied in Task 1 were subjected to ^{13}C and proton NMR analyses, using a home-built solid state NMR spectrometer operating at 100 MH for 'H and 25 MH for ^{13}C. This unit has extensively been used for studies of pyrolyzed pitches and coals supplied by Mobil Oil Research, the Argonne Coal Bank, and Iowa and German coals.

3. RESULTS AND DISCUSSION

3.1 Rheological Properties

Penetration and softening point data of the 60 asphalts from the ten pavement projects are given in Table 2. The variability and changes in asphalts due to hot mixing and laboratory aging as indicated by penetration are shown in Fig. 3. Viscosity data including shear index and complex flow at 25°C are given in Table 3. Shear index or shear susceptibility (the rate of change of viscosity with rate of shear) and complex flow (the rate of change of shear stress with the rate of shear) have been found related to the aging characteristics of asphalts and useful indicators for pavement performance (Kandhal, et al., 1973; Kandhal and Wenger, 1975; and Lee, 1974).

Asphalt cements of high temperature-susceptibility may contribute to rutting at high pavement temperatures and cracking at low pavement temperatures. Temperature susceptibility of an asphalt can be evaluated by penetration ratio, PR (penetration, 4°C, 200 g, 60 sec/penetration, 25°C, 100 g, 5 sec), the Penetration Index (PI), the Pen-Vis Number (PVN) based on viscosity at 60°C or viscosity at 135°C, the viscosity-temperature susceptiblity (VTS), and the Asphalt Class Number (CN). Lower PR, large negative values of PI, lower PVN and greater VTS indicate greater temperature susceptibility. The temperature susceptibility indices in terms of PR, PI, PVN, VTS and CN of the asphalt cement samples studied are given in Table 4. The variabiity and changes in PVN at 60°C of asphalts studied are shown in Fig. 4.

The CN (Bell, 1983) shows the difference between measured and predicted penetration at 25°C. A small negative or positive CN value indicates a Class S (straight run with a straight line, temperature-viscosity-penetration plot) asphalt. High positive CN values indicate Class W (waxy) asphalts, and high negative CN values indicate Class B (blown) asphalts. Either case reflects substantially high and low temperature-susceptibility.

The characteristics most relevant to asphalt performance and indirectly specified in the current ASTM D3381 and AASHTO M226 specifications are temperature-susceptibility and resistance to aging. These important properties are plotted in Fig. 5 in terms of PVN (both 60°C and 135°C) and viscosity ratio at 60°C due to thin film oven treatment. The basic intent is that the most desirable asphalts should be limited to the upper, left corner. These asphalts have the best combination of properties of high resistance to aging and low temperature susceptibility. The ten asphalts supplied in Iowa during the 1988 construction season appeared to be rather uniform and well within the specifications. The significance of these data will be analyzed during Tasks 4 to 6 of the study in relation to chemical changes and performance data.

Low-temperature asphalt stiffness has been correlated with pavement cracking associated with nonload conditions. The low-temperature behavior of asphalts can be evaluated either by estimating the temperature at which asphalt reaches a certain critical or limiting stiffness (the limiting stiffness temperature) or by comparing the stiffness of asphalts at low temperatures and long loading times (The Asphalt Institute, 1981; Kandhal, 1978).

Table 5 presents the results of estimated low-temperature cracking properties of the ten asphalts. The properties include cracking temperature (CT), temperature corresponding to asphalt thermal cracking stress of 72.5 psi (5×10^5 Pa), based on penetrations at 5°C and 25°C, temperature of equivalent asphalt stiffness of 20,000 psi at 10,000 sec loading time (TES), estimated stiffness at -23°C and 10,000 sec loading time, and stiffness at -29°C and 20,000 sec loading time.

Goodrich (1988) found excellent correlation between low-temperature penetration (4°C, 200 g, 60 sec) and limiting stiffness temperature or temperature at which asphalt reaches a critical stiffness (e.g. 20,000 psi at 10,000 sec loading time), defined as temperature of equivalent stiffness (TES) in this study. He also found strong correlations between penetration at 4°C (200 g, 60 sec) and mix flexural fatigue life. Penetration at low temperature appears to be a good indicator for low-temperature cracking and fatigue of asphalt and has been recommended as a criterion for cold climate asphalt specifications.

Statistical values of all properties of the ten asphalts are given in Tables 6a to 6f, grouped by viscosity grades, to show the variability of asphalts supplied in Iowa during the 1988 construction season. While, due to the small sample sizes, these data must be viewed with caution, and the significance of the variability must be interpreted and correlated with performance data, the following general comments can be made:

- There were larger variabilities in AC-20 asphalts than in AC-5 asphalts.
- Within each asphalt grade, there were more differences in stiffness at low temperatures, PI, class number, and PVN, than in cracking temperature, softening point and VTS.
- Laboratory aging seemed to increase the differences among asphalts of the same grade in some properties but decrease the differences in other properties.

Graphical presentations of data in Tables 2-5 for AC-20 asphalts are given in Appendix I.

3.2 HP-GPC Analyses

An interesting development in the field of GPC characterization of asphalts was reported recently by Pribanic et al. (1989) in which the wavelength of detection light is used as a variable. The method comprises using a multichannel UV-visible detector and makes it possible to obtain GPC chromatograms at eight different wavelengths simultaneously in one run. As wavelength scanning provides information on distribution of aromaticity and the functional groups over the molecular size range, this sophistication may prove to be valuable in asphalt characterization.

Garrick and Wood (1988) observed a very significant correlation between HP-GPC data and other physicochemical properties of apshalts if GPC profiles are analysed in terms of fractions of the asphalt in eight adjacent molecular size ranges, rather than three ranges as defined and practiced by the Montana research group (Jennings et al., 1980, 1982, 1985, and 1988) as described in the Task 1 Report of the present project. To explore this possibility and compare the merits of this approach with those of slicing the profile area into three and (as suggested in the progress report) four, we reanalyzed the previously presented HP-GPC data on 24 samples.

First of all, in order to make visual comparisons between samples mathematically more justifiable, the raw GPA chromatograms were normalized by equalizing their areas.

The chromatograms were divided into three Montana type slices, four slices as suggested previously (Lee and Enustun, 1988) and eight slices similar to those put forward by Garrick and Wood (1988). The elution cut-off times used in the first method were 22.5 and 30.5 minutes. The second method is a modification of the first method, in which the LMS fraction is further divided into two using a cut-off elution time of 18.125 minutes. In the

8-slice method the cut off times used were 19.875, 21.875, 23.875, 25.375, 26.875, 28.875 and 30.875 minutes. This slicing is a modified version of that used by Garrick and Wood, and it provides a better correlation with the other asphalt properties.

The asphalt samples related to ten field projects were also analyzed by HP-GPC. The normalized chromatograms of these samples are presented in Appendix II. An inspection of the chromatographic curves reveals that:

(1) Any form of exposure of an asphalt to high temperature in air results in shifting the molecular size distribution to the larger size.

(2) The curves of PAO, PAR and PO intersect each other at a single point, meaning that the mechanisms of TFOT and pressure-oxidation (PO) aging are identical. PO is a more severe form of oxidative aging of TFOT.

Various molecular size fractions obtained by the slicing methods mentioned above, the computed molecular weight and the distribution characteristics and changes due to aging of these samples are given in Tables 7-11. In Tables 7 and 10 the figures in the 5th, 3rd and 4th columns belong to the first, second and third slice, respectively, in the 3-slice method, and those in the 1st, 2nd, 3rd and 4th columns to the respective slices in the 4-slice method.

Multiple regression analyses were performed between HP-GPC parameters defined as percent asphalt in different size fractions and various asphalt properties for Task 1 asphalts. The results are presented in Table 12.

In Tables 13a and 13b we present the results of multiple regression analyses of these data to show the significance of correlation between them and other asphalt properties. These tables include the results of not only various slicing methods, but also the results of one-parameter correlation attempts such as using the Montana LMS rating, the average molecular weight, etc. It appears that the 8-slice method gives the best results, followed by the 4 and 3-slice methods.

3.3 Thermal Analyses

Using the recently acquired DuPont 943 thermomechanical analyzer attached to the Dupont 1090 Thermal Analysis Unit, efforts were made to study systematically the operating conditions of this attachment, the methods of sample preparation and mounting, as well as graphical assessment of the glass transition point (t_g) and thus to establish the optimum conditions to reproduce, as close as possible, the glass transition points of several samples previously obtained by DSC and reported in the Task 1 Report.

A typical TMA plot and the method of locating the glass transition point is shown in Fig. 6.

In Fig. 7 the values of t_g of 12 samples obtained this way are compared with those previously determined by DSC. A good correspondence is shown between the two sets of data.

The t_g results of TMA runs, made with 60 samples related to 10 projects are tabulated in Table 5, together with other low-temperature cracking properties. The t_g values are compared with CT and TES values in Figs. 8 and 9 respectively. Significant correlations of CT and TES with t_g are observable.

3.4 Nuclear Magnetic Resonance (NMR)

The samples studied by NMR spectroscopy were the virgin asphalt sample J10-02-0, its oven treated version J10-02-R and the core samples SC-Bi and WR-Bi from the Sugar Creek and Wood River projects, respectively. The ^{13}C NMR spectra of these samples are shown in Fig. 10, and their proton NMR spectra in Fig. 11. These spectra indicate that:

(1) Oven treatment decreases the amount of aliphatic quaternary carbon in the virgin sample.

(2) The quaternary carbon content of the Sugar Creek sample is strikingly less than those of all other three samples.

(3) The line-width of proton NMR spectra of the Sugar Creek sample is also significantly larger than those of other samples, meaning that this sample is considerably more rigid than the others. It is significant to note that this asphalt was earlier identified as a poor performer.

3.5 Correlations

More than 500 multiple linear regression analyses were performed between physical parameters and molecular weight profiles derived from HP-GPC tests. Table 13a gives r square and level of significance p values for all 53 samples completed to date. Molecular size distribution is best characterized by 8-slice thus correlating well with almost all physical properties. Our results support findings by Garrick and Wood (1988) and Price and Burati (1989) that molecular size profiles derived from HP-GPC data can be used to predict many of the physical properties. Figure 12 compares the actual kinematic viscosity at 135°C with viscosity predicted from regression analysis. Molecular distribution as characterized by large molecular fractions or weighted molecular weights alone did not correlate well with glass transition temperature, cracking temperature, class number and temperature susceptibility in terms of PI, VTS and PVN at 135°C. Regression analyses using only the ten original asphalts showed that the best correlations were obtained using the 4-slice method of treatment of HP-GPC data. Physical properties correlating well with HP-GPC data (at 5% level of significance) were: glass transition temperature, limiting stiffness temperature, penetration at 4°C, low temperature stiffness, penetration ratio, viscosity data and PVN. The properties that did not correlate well with HP-GPC data were: cracking temperature, PI, shear index, complex flow, VTS and viscosity ratio. However, when step-wise linear regression technique was used, dropping insignificant variables, the regressions by 8-sliced method (Table 13b, last column) were considerably improved. For example, the percent in slice 3 effects almost all properties, but glass transition temperature is dependent mainly on the percent in slice 2.

Analysis of correlation data seems to indicate that:

(1) HP-GPC data on original asphalt alone do not provide sufficient information to predict performance. For specification purposes, aged asphalt from accelerated laboratory aging test must be tested to predict performance.

(2) Characterization of asphalt based on only large molecular size fractions is not adequate; complete characterization of the entire molecular size distribution, e.g. the 8-slice method, is needed to more accurately predict the behavior of asphalt by the HP-GPC method.

4. SUMMARY AND CONCLUSIONS

A total of 60 asphalts from ten pavement construction projects, including original asphalts, laboratory aged asphalts, asphalts recovered from field produced mixes and asphalts recovered from laboratory aged mixes, were evaluated by both physical and chemical tests. Additional tests using TMA and NMR techniques and data analyses were also done on Task 1 asphalts. The following conclusions can be drawn:

(1) Asphalts used in the 1988 construction season from a limited number of sources in Iowa showed differences not obvious by either physical tests or chemical tests alone. For example, asphalt used in Project No. 7 had a large percent increase in large molecular size fractions due to aging (TFOT, pressure-oxidation and lab mix aging) but not reflected by changes in physical properties, e.g. viscosity ratio. On the other hand, A.C. No. 11 had a high viscosity ratio after TFOT aging, but not reflected in increase in large molecular size fractions.

(2) The relative significance of the more than 30 physicochemical parameters in predicting the field performance of asphalts can only be established through correlation with field performance data. It is possible that the predictive equation must contain both physical and chemical parameters.

(3) Aging, both in the field and in the laboratory, is accompanied by hardening, reduction in temperature susceptibility by most measures, increase in shear susceptibility, decrease in complex flow, increase in temperature for limiting stiffness, increases in stiffness at low temperatures, increase in large molecular size fractions, increase in molecular weights and decrease in small molecular size fractions.

(4) HP-GPC data are conclusively indicative of aging, and when analyzed over the entire spectra of molecular size distribution by the 8-slice method, can be used to predict behavior and performance of asphalts. However, for specification purposes, both original and laboratory-aged asphalts must be tested.

(5) The glass transition points (t_g) determined by TMA are in general agreement with those determined by differential scanning calorimetry (DSC), and correlate fairly well with low-temperature cracking properties.

(6) Peliminary tests using the NMR techniques showed potential in identifying poor performing asphalt as in the case of core samples from the Sugar Creek project. This method should be pursued in the next phase of the study.

5. RESEARCH PLAN FOR YEAR 3

Research in the third year will continue in Tasks 2 and 3 on evaluation of samples from the ten field projects. Physicochemical parameters of these samples will be correlated with field performance (Task 4). Performance-based asphalt specifications under Iowa conditions will be proposed considering both physical and chemical parameters (Tasks 5 and 6).

In addition, more vigorous investigation for alternative procedures and data interpretation techniques for HP-GPC work will be undertaken for the ten field asphalt samples.

Based on the promising NMR results in identifying the poor quality Sugar Creek sample, additional work using NMR techniques to characterize samples from the ten field projects will be pursued.

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LIST OF TABLES

Table 1. Summary of field samples.

Project	County	AC source	Pavement
1	Monona	AC-10 KOCH, Algona 3/4" AGG. 70% gravel 30% crushed gravel	surface, S[a]
2	Story	AC-20 KOCH, Tama 3/4" AGG. 65% 3/4" crushed limestone 10% 3/8" chips 25% sand	binder, P[b]
3	Dallas	AC-20 KOCH, Dubuque 3/4" AGG. 50% 3/4" crushed gravel 35% 3/4" quartzite 15% concrete sand	surface, I[c]
4	Grundy	AC-5 KOCH, Dubuque 1/2" AGG. 70% 3/4" gravel 12% 3/4" crushed gravel 18% 1/2" crushed limestone	base, S
5	Hardin	AC-5 KOCH, Dubuque 3/4" AGG. 70% 3/4" gravel 30% 3/4" crushed limestone	base, S
7	Webster	AC-5 KOCH, Algona 3/4" AGG. 60% 3/4" crushed limestone 40% 3/4" gravel	base, S
8	Plymouth	AC-5 KOCH, Algona 3/4" AGG. 17% 3/4" wash rock 83% 3/4" pit run	base, S
10	Harrison	AC-20 JEBRO, Sioux City 3/4" AGG. 35% 3/4" quartzite 14% concrete sand 51% 3/4" crushed rock	surface, P
11	Harrison	AC-10 KOCH, Algona 3/4" AGG. 30% 3/4" limestone 30% 3/8" limestone 40% crushed gravel	binder, P
12	Pottawattamie	AC-20 KOCH, Omaha, NE 3/4" AGG. 50% 3/4" stone 35% 3/8" stone 15% sand	binder, I

[a]Secondary road.
[b]Primary road.
[c]Interstate Highway.

Table 2. Rheological properties - I.

sample ID	P5	P25	P4	S.P. C
(AC-5)				
4PAO	19	181	64	41.5
4PAR	14	100	52	45.5
4PO	10	52	25	54.0
4PM	18	144	56	43.5
4PC	15	105	45	46.5
4L35	15	105	54	54.0
4L75	12	55	29	55.0
(AC-5)				
5PAO	18	191	68	41.5
5PAR	13	103	40	48.0
5PO	11	53	25	54.0
5PM	19	156	61	45.5
5L35	12	77	39	51.0
5L75	13	86	37	50.0
(AC-5)				
7PAO	16	193	60	39.0
7PAR	12	94	38	43.5
7PO	10	46	24	56.0
7L35	17	105	44	45.5
7L75	14	91	39	50.0
(AC-5)				
8PAO	17	196	58	38.5
8PAR	13	95	39	46.5
8PO	10	46	25	56.0
8L35	15	88	36	49.5
8L75	14	84	42	50.0
(AC-10)				
1PAO	8	82	29	47.5
1PAR	7	50	21	52.0
1PO	6	27	14	61.5
1PM	10	55	29	56.0
1L35	8	27	15	66.5
1L75	9	32	17	62.5
(AC-10)				
11PAO	15	133	44	44.0
11PAR	10	69	29	51.5
11PO	7	35	21	59.5
11L35	10	60	27	55.0
11L75	11	65	28	54.0

continued

sample ID	P5	P25	P4	S.P. C
(AC-20)				
2PAO	7	54	15	49.0
2PAR	6	38	17	55.5
2PO	6	25	14	67.0
2PM	7	35	18	59.0
2PC	6	30	17	61.0
2LM	7	39	19	60.5
2L35	5	31	16	60.5
2L75	7	35	16	58.5
(AC-20)				
3PAO	9	75	30	47.0
3PAR	8	48	22	54.5
3PO	6	26	14	63.0
3PM	9	41	22	58.0
3PC	9	40	24	58.0
3L35	7	30	16	66.5
3L75	6	33	18	61.5
(AC-20)				
10PAO	9	82	29	49.0
10PAR	7	47	19	50.5
10PO	5	24	14	62.5
10L35	8	32	19	65.0
10L75	10	81	30	48.5
(AC-20)				
12PAO	8	82	28	47.0
12PAR	6	47	20	53.5
12PO	4	23	14	63.0
12L35	9	54	21	56.0
12L50	10	65	27	53.0
12L75	9	51	24	54.0

P5 : penetration @ 5 C, 100 g, 5 sec.
P25 : penetration @ 25 C, 100 g, 5 sec.
P4 : penetration @ 4 C, 200 g, 60 sec.
S.P.: Ring & Ball softening point.

Table 3. Rheological properties - II.

sample ID	VIS 25 poise	C.Flow	S.Index	VIS 60 poise	VIS 135 c.s
(AC-5)					
4PAO	1.50E+05	0.98	0.030	583	250.3
4PAR	7.20E+05	0.96	0.025	1574	368.6
4PO	4.15E+06	0.94	0.080	4682	553.1
4PM	2.90E+06	0.60	0.330	856	1094.8
4PC	5.60E+05	0.92	0.050	1410	361.5
4L35	1.75E+06	0.79	0.220	4457	573.3
4L75	3.80E+06	0.79	0.210	6804	707.2
(AC-5)					
5PAO	1.88E+05	0.96	0.045	632	247.5
5PAR	9.00E+05	0.95	0.060	1470	395.5
5PO	4.75E+06	0.84	0.160	4509	500.1
5PM	4.70E+05	0.91	0.066	1341	285.9
5L35	1.21E+05	0.90	0.100	2368	443.9
5L75	1.23E+06	0.87	0.130	2529	447.1
(AC-5)					
7PAO	2.50E+05	0.99	0.027	734	250.8
7PAR	7.10E+05	0.98	0.023	1742	398.5
7PO	5.25E+06	0.78	0.230	6383	618.7
7L35	4.90E+05	0.89	0.070	1431	388.9
7L75	1.44E+06	0.89	0.110	2324	445.4
(AC-5)					
8PAO	1.86E+05	1.00	0.034	670	253.0
8PAR	7.15E+05	0.98	0.019	1832	404.7
8PO	4.20E+06	0.90	0.100	5080	550.4
8L35	1.40E+06	0.86	0.160	2161	436.2
8L75	1.40E+06	0.89	0.090	3484	500.8
(AC-10)					
1PAO	9.10E+05	0.95	0.045	1576	368.7
1PAR	3.50E+06	0.90	0.100	3722	515.3
1PO	1.55E+07	0.74	0.260	13210	788.4
1PM	2.80E+06	0.82	0.200	6235	664.8
1L35	1.67E+07	0.57	0.420	51768	1431.3
1L75	1.12E+07	0.65	0.390	32534	1185.6
(AC-10)					
11PAO	3.95E+05	0.96	0.037	1110	444.4
11PAR	1.90E+06	0.92	0.070	3558	559.0
11PO	9.50E+06	0.82	0.190	10426	770.3
11L35	3.30E+06	0.83	0.180	4481	638.5
11L75	2.70E+06	0.92	0.090	4220	625.3

continued

sample ID	VIS 25 poise	C.Flow	S.Index	VIS 60 poise	VIS 135 c.s
(AC-20)					
2PAO	3.40E+06	0.94	0.063	3571	889.2
2PAR	8.20E+06	0.72	0.320	6306	986.7
2PO	1.95E+07	0.55	0.460	39716	1654.7
2PM	8.30E+06	0.62	0.350	52329	1975.4
2PC	1.20E+07	0.39	0.580	16986	1384.5
2LM	6.50E+06	0.55	0.440	12315	934.1
2L35	1.40E+07	0.58	0.420	55202	1757.9
2L75	1.15E+07	0.66	0.340	17653	1063.9
(AC-20)					
3PAO	1.17E+06	0.96	0.030	2730	477.3
3PAR	3.60E+06	0.90	0.100	6107	713.3
3PO	1.94E+07	0.72	0.280	21408	1201.6
3PM	4.60E+06	0.81	0.190	15891	1088.2
3PC	6.70E+06	0.72	0.270	13398	964.6
3L35	1.05E+07	0.74	0.260	17218	1039.9
3L75	1.25E+07	0.72	0.290	22750	1183.6
(AC-20)					
10PAO	1.01E+06	0.97	0.030	2105	459.8
10PAR	3.75E+06	0.93	0.070	6334	732.7
10PO	1.85E+07	0.73	0.270	18360	1091.0
10L35	1.20E+07	0.69	0.360	37654	1630.2
10L75	1.53E+06	0.90	0.100	2507	489.5
(AC-20)					
12PAO	1.04E+06	0.98	0.023	2337	470.0
12PAR	4.40E+06	0.91	0.080	6503	774.7
12PO	2.05E+07	0.73	0.260	22624	1139.7
12L35	5.70E+06	0.79	0.200	722	819.7
12L50	4.00E+06	0.89	0.120	4611	715.7
12L75	4.90E+06	0.90	0.100	5489	713.3

VIS 25 : viscosity @ 25 ^{o}C.
S.Index : shear susceptibility index.
C.Flow : complex flow.
VIS 60 : viscosity @ 60 ^{o}C.
VIS 135 : viscosity @ 135 ^{o}C.

Table 4. Temperature susceptibility.

sample ID	PR	PI	CN	VTS	PVN,60	PVN,135
(AC-5)						
4PAO	0.354	0.150	7.963	3.381	-0.367	-0.243
4PAR	0.520	-0.632	2.628	3.474	-0.279	-0.347
4PO	0.481	-0.153	-2.208	3.576	-0.203	-0.466
4PM	0.389	-0.042	27.546	2.384	-0.329	1.907
4PC	0.429	-0.166	3.981	3.445	-0.316	-0.320
4L35	0.514	1.903	-15.241	3.530	0.937	0.396
4L75	0.527	0.212	-8.185	3.527	0.252	-0.070
(AC-5)						
5PAO	0.356	0.400	4.636	3.427	-0.171	-0.190
5PAR	0.388	0.221	5.037	3.387	-0.303	-0.204
5PO	0.472	-0.106	-3.780	3.641	-0.211	-0.585
5PM	0.391	0.983	-7.158	3.624	0.336	-0.211
5L35	0.506	0.153	1.697	3.487	-0.275	-0.364
5L75	0.430	0.214	-2.340	3.507	-0.025	-0.229
(AC-5)						
7PAO	0.311	-0.640	0.980	3.481	0.030	-0.153
7PAR	0.404	-1.461	2.912	3.451	-0.273	-0.300
7PO	0.522	-0.001	-4.995	3.605	-0.089	-0.438
7L35	0.419	-0.478	4.975	3.390	-0.300	-0.207
7L75	0.429	0.388	-1.538	3.477	-0.019	-0.169
(AC-5)						
8PAO	0.296	-0.803	3.073	3.433	-0.051	-0.116
8PAR	0.411	-0.482	1.684	3.459	-0.201	-0.264
8PO	0.543	-0.001	-1.390	3.611	-0.308	-0.594
8L35	0.409	0.148	0.636	3.464	-0.153	-0.239
8L75	0.500	0.144	-7.584	3.542	0.273	-0.087
(AC-10)						
1PAO	0.354	-0.620	7.221	3.474	-0.599	-0.569
1PAR	0.420	-0.711	3.467	3.544	-0.485	-0.602
1PO	0.519	-0.053	-5.255	3.684	-0.189	-0.626
1PM	0.527	0.434	-7.211	3.542	0.166	-0.155
1L35	0.556	0.818	-28.138	3.718	1.029	0.108
1L75	0.531	0.476	-24.338	3.697	0.875	0.044
(AC-10)						
11PAO	0.331	-0.165	8.504	3.175	-0.174	0.307
11PAR	0.420	-0.026	-1.686	3.463	-0.033	-0.151
11PO	0.600	0.103	-6.383	3.618	-0.034	-0.417
11L35	0.450	0.436	-1.676	3.449	-0.024	-0.117
11L75	0.431	0.419	-2.453	3.442	0.044	-0.057

continued

sample ID	PR	PI	CN	VTS	PVN,60	PVN,135
(AC-20)						
2PAO	0.278	-1.276	13.393	3.116	-0.411	0.226
2PAR	0.447	-0.534	10.235	3.255	-0.382	-0.016
2PO	0.560	0.746	-16.497	3.535	0.676	0.209
2PM	0.514	0.005	-27.443	3.507	1.457	0.790
2PC	0.567	0.066	-2.815	3.372	0.187	0.173
2LM	0.487	0.534	-9.454	3.536	0.283	-0.060
2L35	0.516	0.039	-28.427	3.601	1.306	0.507
2L75	0.457	-0.093	-13.336	3.568	0.453	-0.003
(AC-20)						
3PAO	0.400	-1.008	0.067	3.485	-0.170	-0.287
3PAR	0.458	-0.230	-1.974	3.481	-0.067	-0.203
3PO	0.538	0.142	-8.030	3.548	0.187	-0.144
3PM	0.537	0.153	-14.002	3.516	0.601	0.193
3PC	0.600	0.097	-11.564	3.542	0.402	0.008
3L35	0.533	1.038	-9.235	3.575	0.199	-0.185
3L75	0.545	0.357	-16.154	3.579	0.596	0.073
(AC-20)						
10PAO	0.354	-0.199	3.939	3.411	-0.296	-0.241
10PAR	0.404	-1.211	-1.850	3.474	-0.064	-0.189
10PO	0.583	-0.100	-3.586	3.563	-0.062	-0.336
10L35	0.594	0.920	-21.449	3.528	1.009	0.446
10L75	0.370	-0.372	0.946	3.431	-0.133	-0.163
(AC-20)						
12PAO	0.341	-0.764	1.676	3.436	-0.186	-0.209
12PAR	0.426	-0.505	-1.415	3.443	-0.038	-0.114
12PO	0.609	-0.092	-7.215	3.603	0.062	-0.322
12L35	0.389	0.388	58.905	2.518	-1.981	0.114
12L50	0.415	0.181	-2.116	3.373	0.133	0.134
12L75	0.471	-0.200	-0.724	3.441	-0.077	-0.139

PR : penetration ratio, P4/P25.
PI : penetration index.
CN : class number.
VTS : viscosity-temperature susceptibility.
PVN,60 : penetration-viscosity number @ 60 C.
PVN,135 : penetration-viscosity number @ 135 C.

Table 5. Low-temperature cracking properties.

sample ID	TMA Tg, °C	CT °C	TES °C	S,-23 ksi	S,-29 ksi
(AC-5)					
4PAO	-31.3	-43.5	-49.0	0.189	0.508
4PAR	-30.3	-44.0	-38.0	1.740	3.625
4PO	-27.3	-43.0	-33.5	4.350	9.425
4PM	-29.5	-47.0	-44.5	0.399	0.870
4PC	-29.3	-44.0	-40.5	1.088	2.175
4L35	-33.5	-48.0	-55.0	0.363	0.580
4L75	-33.3	-46.0	-36.0	2.900	5.438
(AC-5)					
5PAO	-30.0	-42.5	-51.5	0.109	0.363
5PAR	-36.3	-41.5	-43.0	0.943	1.813
5PO	-34.0	-44.0	-33.5	4.060	7.975
5PM	-31.3	-45.0	-54.5	0.247	0.363
5L35	-30.5	-41.0	-39.5	1.450	2.900
5L75	-32.5	-43.5	-41.0	1.088	2.320
(AC-5)					
7PAO	-34.0	-39.0	-44.0	0.218	0.725
7PAR	-26.8	-39.0	-32.0	3.625	8.700
7PO	-28.5	-45.0	-32.5	5.075	10.150
7L35	-31.0	-45.5	-39.0	1.305	2.900
7L75	-37.0	-41.5	-43.0	1.088	1.885
(AC-5)					
8PAO	-26.8	-40.0	-43.5	0.363	1.160
8PAR	-29.9	-42.5	-38.0	1.160	2.900
8PO	-30.9	-45.0	-32.5	4.785	8.700
8L35	-32.0	-46.5	-40.5	1.088	2.320
8L75	-33.3	-46.5	-40.0	1.160	2.610
(AC-10)					
1PAO	-33.0	-35.0	-36.0	2.610	5.800
1PAR	-22.5	-36.0	-30.5	6.090	12.325
1PO	-27.5	-40.0	-26.0	13.050	21.750
1PM	-31.9	-42.5	-37.0	2.900	5.800
1L35	-28.0	-47.5	-49.5	7.250	12.325
1L75	-28.0	-47.5	-48.5	7.250	11.600
(AC-10)					
11PAO	-27.5	-42.5	-43.0	0.508	1.450
11PAR	-28.0	-40.0	-37.0	2.175	4.350
11PO	-24.0	-40.0	-29.5	6.525	13.050
11L35	-34.0	-41.5	-38.0	2.320	5.075
11L75	-25.5	-42.5	-39.0	2.175	3.915

continued

sample ID	TMA Tg, °C	CT °C	TES °C	S,-23 ksi	S,-29 ksi
(AC-20)					
2PAO	-25.0	-36.0	-28.0	10.875	24.650
2PAR	-28.5	-35.5	-28.5	10.875	21.750
2PO	-28.3	-40.0	-30.0	8.700	14.500
2PM	-27.8	-40.0	-29.5	7.250	14.500
2PC	-32.5	-37.5	-28.0	9.425	21.750
2LM	-29.9	-38.5	-34.0	5.075	8.700
2L35	-33.3	-34.0	-28.5	10.150	18.850
2L75	-33.9	-40.0	-31.0	8.700	14.500
(AC-20)					
3PAO	-22.5	-37.5	-33.0	4.350	9.425
3PAR	-27.0	-39.0	-32.0	5.075	10.875
3PO	-22.0	-40.0	-27.0	11.600	20.300
3PM	-29.4	-44.0	-32.0	5.075	10.150
3PC	-33.0	-44.0	-31.5	5.365	10.440
3L35	-27.5	-42.5	-34.0	5.800	10.875
3L75	-25.3	-37.0	-31.0	7.250	13.050
(AC-20)					
10PAO	-23.5	-37.0	-38.0	1.740	3.770
10PAR	-22.5	-37.0	-27.5	9.425	21.750
10PO	-28.5	-36.5	-25.0	14.500	24.650
10L35	-31.0	-45.0	-34.0	5.220	8.700
10L75	-32.0	-38.5	-37.0	2.320	5.365
(AC-20)					
12PAO	-24.0	-35.0	-35.0	2.900	5.510
12PAR	-25.0	-34.0	-31.0	5.510	10.875
12PO	-21.5	-32.5	-24.5	15.950	24.650
12L35	-28.0	-42.5	-37.0	2.900	5.510
12L50	-27.3	-41.0	-37.5	2.175	4.350
12L75	-28.3	-41.5	-33.0	4.350	7.975

Tg : glass transition temperature.
CT : cracking temperature.
TES : temperature of equivalent stiffness at 20 ksi and 10,000 sec.
S,-23 : stiffness at -23 °C and 10,000 sec.
S,-29 : stiffness at -29 °C and 20,000 sec.

Table 6a. Statistical values for all data - PAO, AC-5.

Variable	Mean	Std Dev	Min.	Max.	Coeff.of Var.
		Rheological properties			
P5	17.50	1.29	16.00	19.00	7.38
P25	190.25	6.50	181.00	196.00	3.42
P4	62.50	4.43	58.00	68.00	7.10
S.P.	40.13	1.60	38.50	41.50	3.99
VIS 25	1.94E+05	41517	1.50E+05	2.50E+05	21.46
C.Flow	0.98	0.02	0.96	1.00	1.74
S.Index	0.03	0.01	0.03	0.05	23.16
VIS 60	654.75	63.71	583.00	734.00	9.73
VIS135	250.40	2.26	247.50	253.00	0.90
		Low-temperature properties			
Tg	-30.50	3.01	-34.00	-26.75	9.86
CT	-41.25	2.10	-43.50	-39.00	5.09
TES	-47.00	3.89	-51.50	-43.50	8.29
S23	0.22	0.11	0.11	0.36	48.31
S29	0.69	0.35	0.36	1.16	50.48
		Temperature susceptibility			
PR	0.33	0.03	0.30	0.36	9.21
PI	-0.22	0.59	-0.80	0.40	263.35
CN	4.16	2.94	0.98	7.96	70.70
VTS	3.43	0.04	3.38	3.48	1.20
PVN,60	-0.14	0.17	-0.37	0.03	123.56
PVN,135	-0.18	0.05	-0.24	-0.12	30.80
		HP-GPC			
LMS	3.36	1.48	1.16	4.37	44.07
MMS1	26.79	2.65	22.83	28.38	9.91
MMS2	59.08	2.45	57.62	62.75	4.15
SMS	10.77	1.67	9.80	13.26	15.50
X1	11.93	3.04	7.39	13.80	25.48
X2	14.18	0.94	12.78	14.83	6.67
X3	17.07	0.39	16.50	17.40	2.30
X4	13.47	0.20	13.29	13.77	1.52
X5	12.50	0.48	12.21	13.21	3.83
X6	13.29	1.12	12.67	14.96	8.42
X7	8.50	1.15	7.85	10.21	13.49
X8	9.08	1.41	8.25	11.19	15.58
LMS+MMS1	30.15	4.12	23.99	32.58	13.66
WTMWT	5677	1434.41	3542	6631	25.27
ZMWT	34213	10002.28	19380	41076	29.24
Z1MWT	67765	19571.33	38578	80470	28.88
POLYIDX	10.28	1.81	7.60	11.48	17.59

Table 6b. Statistical values for all data - PAR, AC-5.

Variable	Mean	Std Dev	Min.	Max.	Coeff.of Var.
		Rheological properties			
P5	13.00	0.82	12.00	14.00	6.28
P25	98.00	4.24	94.00	103.00	4.33
P4	42.25	6.55	38.00	52.00	15.51
S.P.	45.88	1.89	43.50	48.00	4.11
VIS 25	7.61E+05	92590	7.10E+05	9.00E+05	12.16
C.Flow	0.97	0.01	0.95	0.98	1.55
S.Index	0.03	0.02	0.02	0.06	59.84
VIS 60	1654.50	162.98	1470.00	1832.00	9.85
VIS135	391.83	15.95	368.60	404.70	4.07
		Low-temperature properties			
Tg	-30.79	3.97	-36.25	-26.75	12.89
CT	-41.75	2.10	-44.00	-39.00	5.03
TES	-37.75	4.50	-43.00	-32.00	11.92
S23	1.87	1.22	0.94	3.63	65.32
S29	4.26	3.05	1.81	8.70	71.67
		Temperature susceptibility			
PR	0.43	0.06	0.39	0.52	13.98
PI	-0.59	0.69	-1.46	0.22	117.31
CN	3.07	1.42	1.68	5.04	46.17
VTS	3.44	0.04	3.39	3.47	1.11
PVN,60	-0.26	0.04	-0.30	-0.20	16.63
PVN,135	-0.28	0.06	-0.35	-0.20	21.70
		HP-GPC			
LMS	6.06	0.28	5.72	6.30	4.56
MMS1	29.58	0.17	29.34	29.75	0.58
MMS2	54.71	0.33	54.46	55.16	0.60
SMS	9.65	0.11	9.52	9.79	1.16
X1	16.77	0.45	16.20	17.14	2.67
X2	14.86	0.05	14.82	14.93	0.33
X3	16.54	0.10	16.44	16.67	0.59
X4	12.64	0.10	12.55	12.76	0.79
X5	11.52	0.07	11.44	11.61	0.59
X6	12.00	0.08	11.91	12.10	0.63
X7	7.53	0.04	7.50	7.58	0.48
X8	8.14	0.10	8.02	8.27	1.28
LMS+MMS1	35.64	0.43	35.06	36.02	1.22
WTMWT	8162	227.03	7880	8346	2.78
ZMWT	48106	568.66	47609	48628	1.18
Z1MWT	88862	1086.30	87889	90409	1.22
POLYIDX	13.68	0.27	13.36	13.93	1.96

Table 6c. Statistical values for all data - PAO, AC-10.

Variable	Mean	Std Dev	Min.	Max.	Coeff.of Var.
			Rheological properties		
P5	11.50	4.95	8.00	15.00	43.04
P25	107.50	36.06	82.00	133.00	33.55
P4	36.50	10.61	29.00	44.00	29.06
S.P.	45.75	2.47	44.00	47.50	5.41
VIS 25	6.53E+05	364160	3.95E+05	9.10E+05	55.81
C.Flow	0.96	0.01	0.95	0.96	0.74
S.Index	0.04	0.01	0.04	0.05	13.80
VIS 60	1343.00	329.51	1110.00	1576.00	24.54
VIS135	406.55	53.53	368.70	444.40	13.17
			Low-temperature properties		
Tg	-30.25	3.89	-33.00	-27.50	12.86
CT	-38.75	5.30	-42.50	-35.00	13.69
TES	-39.50	4.95	-43.00	-36.00	12.53
S23	1.56	1.49	0.51	2.61	95.38
S29	3.63	3.08	1.45	5.80	84.85
			Temperature susceptibility		
PR	0.34	0.02	0.33	0.35	4.72
PI	-0.39	0.32	-0.62	-0.17	81.89
CN	7.86	0.91	7.22	8.50	11.54
VTS	3.32	0.21	3.17	3.47	6.37
PVN,60	-0.39	0.30	-0.60	-0.17	77.74
PVN,135	-0.13	0.62	-0.57	0.31	472.35
		HP-GPC			
LMS	3.57	0.30	3.35	3.78	8.43
MMS1	27.11	2.01	25.69	28.53	7.40
MMS2	59.59	2.30	57.97	61.21	3.85
SMS	9.73	0.01	9.72	9.74	0.14
X1	12.45	1.13	11.65	13.25	9.07
X2	14.16	1.02	13.44	14.88	7.24
X3	17.39	0.22	17.23	17.55	1.27
X4	13.92	0.60	13.50	14.34	4.29
X5	12.81	0.68	12.33	13.29	5.31
X6	13.14	0.83	12.55	13.73	6.32
X7	7.95	0.29	7.75	8.16	3.64
X8	8.18	0.02	8.16	8.19	0.25
LMS+MMS1	30.68	2.31	29.05	32.31	7.52
WTMWT	5860	412.24	5568	6151	7.04
ZMWT	35755	26.87	35736	35774	0.08
Z1MWT	70490	738.93	69967	71012	1.05
POLYIDX	10.29	0.47	9.96	10.63	4.55

Table 6d. Statistical values for all data - PAR, AC-10.

Variable	Mean	Std Dev	Min.	Max.	Coeff.of Var.
		Rheological properties			
P5	8.50	2.12	7.00	10.00	24.96
P25	59.50	13.44	50.00	69.00	22.58
P4	25.00	5.66	21.00	29.00	22.63
S.P.	51.75	0.35	51.50	52.00	0.68
VIS 25	2.70E+06	1131371	1.90E+06	3.50E+06	41.90
C.Flow	0.91	0.01	0.90	0.92	1.55
S.Index	0.09	0.02	0.07	0.10	24.96
VIS 60	3640.00	115.97	3558.00	3722.00	3.19
VIS135	537.15	30.90	515.30	559.00	5.75
		Low-temperature properties			
Tg	-25.25	3.89	-28.00	-22.50	15.40
CT	-38.00	2.83	-40.00	-36.00	7.44
TES	-33.75	4.60	-37.00	-30.50	13.62
S23	4.13	2.77	2.18	6.09	66.99
S29	8.34	5.64	4.35	12.33	67.64
		Temperature susceptibility			
PR	0.42	0.00	0.42	0.42	0.05
PI	-0.37	0.48	-0.71	-0.03	131.43
CN	0.89	3.64	-1.69	3.47	409.01
VTS	3.50	0.06	3.46	3.54	1.64
PVN,60	-0.26	0.32	-0.49	-0.03	123.45
PVN,135	-0.38	0.32	-0.60	-0.15	84.76
		HP-GPC			
LMS	5.30	1.09	4.53	6.07	20.62
MMS1	28.86	1.94	27.49	30.23	6.71
MMS2	56.48	2.83	54.48	58.48	5.01
SMS	9.37	0.20	9.23	9.51	2.12
X1	15.45	2.22	13.88	17.02	14.35
X2	14.67	0.74	14.15	15.19	5.04
X3	16.83	0.05	16.80	16.87	0.28
X4	13.18	0.68	12.70	13.65	5.13
X5	12.08	0.87	11.46	12.69	7.21
X6	12.39	0.87	11.77	13.01	7.03
X7	7.52	0.35	7.28	7.76	4.59
X8	7.89	0.15	7.78	7.99	1.85
LMS+MMS1	34.15	3.03	32.01	36.30	8.87
WTMWT	7457	1071.97	6699	8215	14.38
ZMWT	44673	3583.62	42139	47207	8.02
Z1MWT	83974	4161.32	81031	86916	4.96
POLYIDX	12.49	1.31	11.56	13.41	10.47

Table 6e. Statistical values for all data - PAO, AC-20.

Variable	Mean	Std Dev	Min.	Max.	Coeff.of Var.
		Rheological properties			
P5	8.25	0.96	7.00	9.00	11.61
P25	73.25	13.25	54.00	82.00	18.09
P4	25.50	7.05	15.00	30.00	27.64
S.P.	48.00	1.15	47.00	49.00	2.41
VIS 25	1.66E+06	1165404	1.01E+06	3.40E+06	70.42
C.Flow	0.96	0.02	0.94	0.98	1.77
S.Index	0.04	0.02	0.02	0.06	49.24
VIS 60	2685.75	644.08	2105.00	3571.00	23.98
VIS135	574.08	210.21	459.80	889.20	36.62
		Low-temperature properties			
Tg	-23.75	1.04	-25.00	-22.50	4.38
CT	-36.38	1.11	-37.50	-35.00	3.05
TES	-33.50	4.20	-38.00	-28.00	12.55
S23	4.97	4.08	1.74	10.88	82.18
S29	10.84	9.51	3.77	24.65	87.71
		Temperature susceptibility			
PR	0.34	0.05	0.28	0.40	14.68
PI	-0.81	0.46	-1.28	-0.20	56.56
CN	4.77	5.96	0.07	13.39	125.08
VTS	3.36	0.17	3.12	3.48	4.96
PVN,60	-0.27	0.11	-0.41	-0.17	42.06
PVN,135	-0.13	0.24	-0.29	0.23	186.14
		HP-GPC			
LMS	4.32	0.27	3.93	4.56	6.31
MMS1	29.72	1.13	28.75	31.34	3.80
MMS2	57.33	0.47	56.89	57.96	0.82
SMS	8.64	0.98	7.21	9.37	11.29
X1	14.24	0.58	13.46	14.87	4.10
X2	15.47	0.64	15.04	16.42	4.16
X3	18.07	0.79	17.63	19.25	4.35
X4	13.77	0.49	13.42	14.49	3.54
X5	12.21	0.16	12.05	12.40	1.28
X6	11.96	0.70	10.93	12.47	5.85
X7	6.98	0.71	5.92	7.46	10.24
X8	7.29	0.82	6.08	7.90	11.26
LMS+MMS1	34.03	1.35	32.68	35.90	3.98
WTMWT	6746	368.23	6313	7210	5.46
ZMWT	39622	2582.51	37329	43210	6.52
Z1MWT	78651	7634.93	73987	90018	9.71
POLYIDX	10.83	0.32	10.44	11.13	2.95

Table 6f. Statistical values for all data - PAR, AC-20.

Variable	Mean	Std Dev	Min.	Max.	Coeff. of Var.
			Rheological properties		
P5	6.75	0.96	6.00	8.00	14.18
P25	45.00	4.69	38.00	48.00	10.42
P4	19.50	2.08	17.00	22.00	10.68
S.P.	53.50	2.16	50.50	55.50	4.04
VIS 25	4.99E+06	2169629	3.60E+06	8.20E+06	43.50
C.Flow	0.87	0.10	0.72	0.93	11.27
S.Index	0.14	0.12	0.07	0.32	83.50
VIS 60	6312.50	162.30	6107.00	6503.00	2.57
VIS135	801.85	125.87	713.30	986.70	15.70
			Low-temperature properties		
Tg	-25.75	2.60	-28.50	-22.50	10.09
CT	-36.38	2.14	-39.00	-34.00	5.87
TES	-29.75	2.10	-32.00	-27.50	7.06
S23	7.72	2.87	5.08	10.88	37.19
S29	16.31	6.28	10.88	21.75	38.49
			Temperature susceptibility		
PR	0.43	0.02	0.40	0.46	5.53
PI	-0.62	0.42	-1.21	-0.23	67.28
CN	1.25	6.00	-1.97	10.23	479.99
VTS	3.41	0.11	3.26	3.48	3.12
PVN,60	-0.14	0.16	-0.38	-0.04	118.67
PVN,135	-0.13	0.09	-0.20	-0.02	65.95
			HP-GPC		
LMS	6.39	0.20	6.17	6.59	3.17
MMS1	31.36	1.40	30.48	33.46	4.46
MMS2	54.01	0.38	53.48	54.39	0.71
SMS	8.23	0.90	6.90	8.87	10.95
X1	17.74	0.28	17.35	18.02	1.60
X2	15.80	0.83	15.31	17.04	5.24
X3	17.34	0.84	16.90	18.60	4.84
X4	12.96	0.38	12.74	13.53	2.94
X5	11.45	0.14	11.25	11.59	1.26
X6	11.20	0.66	10.22	11.64	5.90
X7	6.56	0.71	5.50	7.02	10.82
X8	6.95	0.75	5.85	7.49	10.76
LMS+MMS1	37.76	1.28	36.76	39.63	3.38
WTMWT	8652	144.11	8437	8735	1.67
ZMWT	49112	726.95	48435	49779	1.48
Z1MWT	91584	1658.09	89927	93885	1.81
POLYIDX	13.18	0.79	12.00	13.68	6.02

Table 7. HP-GPC results, 3-slice and 4-slice methods.

sample ID	LMS	MMS1	MMS2	SMS	LMS+MMS1
(AC-5)					
4PAO	4.37	28.21	57.62	9.80	32.58
4PAR	6.27	29.75	54.46	9.52	36.02
4PO	7.65	30.54	52.74	9.07	38.19
4PM	4.81	30.46	55.04	9.69	35.28
4PC	3.97	28.74	57.48	9.82	32.71
4L35	5.27	30.60	54.96	9.18	35.86
4L75	6.10	31.47	53.71	8.71	37.57
(AC-5)					
5PAO	4.07	27.73	58.04	10.16	31.80
5PAR	6.30	29.62	54.46	9.62	35.92
5PO	7.80	30.74	52.46	9.00	38.54
5PM	3.94	29.78	56.92	9.36	33.72
5L35	5.90	30.83	54.41	8.87	36.73
(AC-5)					
7PAO	1.16	22.83	62.75	13.26	23.99
7PAR	5.72	29.34	55.16	9.79	35.06
7PO	7.55	30.81	52.48	9.16	38.36
7L35	5.14	29.82	55.58	9.47	34.96
(AC-5)					
8PAO	3.84	28.38	57.93	9.86	32.22
8PAR	5.96	29.62	54.77	9.66	35.57
8PO	6.85	30.42	53.53	9.20	37.27
8L35	4.94	29.97	55.63	9.46	34.91
(AC-10)					
1PAO	3.35	25.69	61.21	9.74	29.05
1PAR	4.53	27.49	58.48	9.51	32.01
1PO	5.60	29.07	56.63	8.70	34.67
1PM	3.62	28.80	57.98	9.60	32.42
1L35	4.43	29.45	56.98	9.13	33.89
1L75	3.05	28.40	58.74	9.81	31.45
(AC-10)					
11PAO	3.78	28.53	57.97	9.72	32.31
11PAR	6.07	30.23	54.48	9.23	36.30
11PO	7.07	30.98	52.97	8.98	38.05
11L35	5.18	29.84	55.31	9.67	35.02

continued

sample ID	LMS	MMS1	MMS2	SMS	LMSMMS1
(AC-20)					
2PAO	4.56	31.34	56.89	7.21	35.90
2PAR	6.17	33.46	53.48	6.90	39.63
2PO	7.45	35.22	50.98	6.36	42.66
2PM	5.72	34.48	52.86	6.95	40.19
2PC	5.83	34.44	52.79	6.94	40.27
2LM	5.91	33.08	53.31	7.70	38.99
2L35	5.99	33.69	53.04	7.29	39.68
2L75	5.77	33.10	53.48	7.66	38.87
(AC-20)					
3PAO	4.44	29.25	57.40	8.91	33.68
3PAR	6.59	30.77	54.15	8.49	37.36
3PO	7.98	31.86	52.24	7.92	39.84
3PM	4.61	31.16	55.05	9.19	35.77
3PC	4.30	30.81	56.13	8.76	35.11
3L35	5.72	31.77	54.17	8.35	37.49
3L75	5.96	32.19	53.60	8.26	38.15
(AC-20)					
10PAO	3.93	28.75	57.96	9.37	32.68
10PAR	6.27	30.48	54.39	8.87	36.76
10PO	7.34	31.11	52.95	8.60	38.45
10L35	11.28	31.66	49.35	7.70	42.94
(AC-20)					
12PAO	4.33	29.53	57.06	9.09	33.86
12PAR	6.54	30.75	54.04	8.67	37.29
12PO	7.49	31.55	52.55	8.42	39.03
12L35	5.58	30.63	54.71	9.08	36.21

Table 8. HP-GPC results, 8-slice method.

sample ID	X1	X2	X3	X4	X5	X6	X7	X8
(AC-5)								
4PAO	13.80	14.68	17.24	13.29	12.21	12.67	7.87	8.25
4PAR	17.14	14.88	16.49	12.56	11.50	11.91	7.50	8.02
4PO	19.20	15.07	16.11	12.17	11.04	11.55	7.24	7.62
4PM	15.13	15.70	17.83	12.73	11.33	11.70	7.39	8.20
4PC	13.45	15.04	17.56	13.31	12.04	12.49	7.87	8.24
4L35	16.17	15.52	17.30	12.77	11.49	11.74	7.28	7.74
4L75	17.57	15.78	17.22	12.57	11.16	11.37	7.02	7.32
(AC-5)								
5PAO	13.30	14.42	17.13	13.40	12.30	12.83	8.06	8.56
5PAR	17.12	14.82	16.44	12.55	11.44	11.98	7.53	8.11
5PO	19.56	15.04	16.07	12.10	10.97	11.50	7.18	7.57
5PM	13.65	15.63	18.09	13.22	11.82	12.16	7.59	7.85
5L35	17.10	15.50	16.91	12.64	11.37	11.76	7.32	7.41
(AC-5)								
7PAO	7.39	12.78	16.50	13.77	13.21	14.96	10.21	11.19
7PAR	16.20	14.83	16.67	12.76	11.61	12.10	7.58	8.27
7PO	19.29	15.11	16.16	12.12	11.01	11.42	7.15	7.73
7L35	15.66	15.17	17.08	12.89	11.72	12.06	7.45	7.99
(AC-5)								
8PAO	13.24	14.83	17.40	13.43	12.26	12.69	7.85	8.31
8PAR	16.63	14.93	16.58	12.68	11.51	12.00	7.52	8.16
8PO	18.27	15.04	16.33	12.38	11.25	11.69	7.29	7.75
8L35	15.41	15.33	17.21	12.90	11.65	12.07	7.47	7.97
(AC-10)								
1PAO	11.65	13.44	17.23	14.34	13.29	13.73	8.16	8.16
1PAR	13.88	14.15	16.87	13.65	12.69	13.01	7.76	7.99
1PO	16.04	14.66	16.69	13.19	12.28	12.57	7.23	7.34
1PM	12.97	15.10	17.90	13.42	12.20	12.58	7.78	8.06
1L35	14.52	15.22	17.43	13.30	12.11	12.33	7.41	7.69
1L75	12.23	14.97	17.74	13.54	12.45	12.93	7.89	8.26
(AC-10)								
11PAO	13.25	14.88	17.55	13.50	12.33	12.55	7.75	8.19
11PAR	17.02	15.19	16.80	12.70	11.46	11.77	7.28	7.78
11PO	18.71	15.31	16.46	12.32	11.13	11.43	7.06	7.58
11L35	15.70	15.24	17.03	12.95	11.52	11.97	7.39	8.20

continued

sample ID	X1	X2	X3	X4	X5	X6	X7	X8
(AC-20)								
2PAO	14.87	16.42	19.25	14.49	12.05	10.93	5.92	6.08
2PAR	18.02	17.04	18.60	13.53	11.25	10.22	5.50	5.85
2PO	20.53	17.61	18.06	12.84	10.69	9.78	5.09	5.41
2PM	17.82	17.65	18.90	13.41	10.96	9.96	5.37	5.92
2PC	18.24	17.42	18.79	13.32	10.99	9.93	5.42	5.90
2LM	17.75	16.79	18.03	13.08	11.20	10.58	6.03	6.53
2L35	18.20	17.03	18.18	13.05	11.09	10.44	5.87	6.16
2L75	17.69	16.76	18.03	13.09	11.27	10.62	6.05	6.49
(AC-20)								
3PAO	14.32	15.13	17.70	13.54	12.28	12.26	7.27	7.50
3PAR	17.85	15.44	16.90	12.80	11.59	11.45	6.82	7.15
3PO	20.15	15.68	16.44	12.30	11.15	11.18	6.40	6.71
3PM	15.04	16.16	18.24	12.92	11.43	11.48	6.92	7.82
3PC	14.43	16.06	18.52	13.21	11.67	11.71	7.03	7.37
3L35	17.19	16.02	17.49	12.90	11.41	11.28	6.66	7.05
3L75	17.60	16.24	17.60	12.80	11.21	11.06	6.54	6.96
(AC-20)								
10PAO	13.46	15.04	17.63	13.65	12.40	12.47	7.46	7.90
10PAR	17.35	15.31	16.92	12.77	11.51	11.64	7.02	7.49
10PO	19.10	15.32	16.53	12.43	11.23	11.32	6.82	7.26
10L35	23.78	15.27	15.80	11.60	10.37	10.46	6.27	6.46
(AC-20)								
12PAO	14.34	15.29	17.70	13.42	12.12	12.20	7.27	7.66
12PAR	17.76	15.40	16.94	12.74	11.45	11.51	6.89	7.32
12PO	19.42	15.54	16.58	12.40	11.10	11.16	6.69	7.11
12L35	16.57	15.47	17.24	12.80	11.50	11.64	7.08	7.68

Table 9. HP-GPC results - molecular weight distribution characteristics.

sample ID	WTMWT	ZMWT	Z1MWT	POLYIDX	HPVIS
(AC-5)					
4PAO	6.63E+03	4.11E+04	8.05E+04	11.484	6.63E+03
4PAR	8.35E+03	4.86E+04	8.87E+04	13.857	8.35E+03
4PO	9.61E+03	5.41E+04	9.59E+04	15.318	9.61E+03
4PM	7.23E+03	4.37E+04	9.13E+04	12.073	7.23E+03
4PC	6.42E+03	4.09E+04	9.01E+04	11.061	6.41E+03
4L35	7.53E+03	4.16E+04	7.70E+04	12.270	7.53E+03
4L75	8.35E+03	4.64E+04	8.81E+04	13.080	8.35E+03
(AC-5)					
5PAO	6.33E+03	3.90E+04	7.60E+04	11.211	6.33E+03
5PAR	8.35E+03	4.86E+04	8.79E+04	13.934	8.35E+03
5PO	9.76E+03	5.45E+04	9.73E+04	15.466	9.76E+03
5PM	6.50E+03	4.11E+04	9.49E+04	10.859	6.50E+03
5L35	8.14E+03	4.63E+04	8.85E+04	12.989	8.14E+03
(AC-5)					
7PAO	3.54E+03	1.94E+04	3.86E+04	7.596	3.54E+03
7PAR	7.88E+03	4.76E+04	9.04E+04	13.359	7.88E+03
7PO	9.50E+03	5.22E+04	9.16E+04	15.184	9.50E+03
7L35	7.37E+03	4.21E+04	7.85E+04	12.298	7.37E+03
(AC-5)					
8PAO	6.21E+03	3.74E+04	7.60E+04	10.813	6.21E+03
8PAR	8.08E+03	4.76E+04	8.84E+04	13.553	8.08E+03
8PO	8.87E+03	4.96E+04	8.90E+04	14.359	8.87E+03
8L35	7.23E+03	4.13E+04	7.80E+04	12.055	7.23E+03
(AC-10)					
1PAO	5.57E+03	3.57E+04	7.10E+04	9.962	5.57E+03
1PAR	6.70E+03	4.21E+04	8.10E+04	11.562	6.70E+03
1PO	7.70E+03	4.50E+04	8.27E+04	12.537	7.69E+03
1PM	6.10E+03	3.76E+04	8.33E+04	10.456	6.10E+03
1L35	6.76E+03	3.85E+04	7.28E+04	11.234	6.76E+03
1L75	5.54E+03	3.03E+04	5.88E+04	9.698	5.54E+03
(AC-10)					
11PAO	6.15E+03	3.58E+04	7.00E+04	10.625	6.15E+03
11PAR	8.22E+03	4.72E+04	8.69E+04	13.410	8.21E+03
11PO	9.15E+03	5.10E+04	9.17E+04	14.525	9.15E+03
11L35	7.37E+03	4.16E+04	7.72E+04	12.395	7.37E+03

continued

sample ID	WTMWT	ZMWT	Z1MWT	POLYIDX	HPVIS
(AC-20)					
2PAO	7.21E+03	4.32E+04	9.00E+04	10.444	7.21E+03
2PAR	8.74E+03	4.84E+04	9.39E+04	11.999	8.74E+03
2PO	9.95E+03	5.13E+04	9.51E+04	12.890	9.95E+03
2PM	8.38E+03	4.43E+04	8.80E+04	11.440	8.38E+03
2PC	8.54E+03	4.54E+04	9.05E+04	11.640	8.54E+03
2LM	8.47E+03	4.76E+04	9.67E+04	12.304	8.47E+03
2L35	8.50E+03	4.41E+04	8.26E+04	11.988	8.49E+03
2L75	8.33E+03	4.58E+04	9.20E+04	12.096	8.33E+03
(AC-20)					
3PAO	6.77E+03	3.97E+04	7.61E+04	11.126	6.77E+03
3PAR	8.74E+03	4.97E+04	9.13E+04	13.591	8.74E+03
3PO	1.00E+04	5.39E+04	9.54E+04	14.840	1.00E+04
3PM	7.13E+03	4.23E+04	9.03E+04	11.575	7.13E+03
3PC	6.86E+03	4.13E+04	9.07E+04	10.960	6.85E+03
3L35	8.03E+03	4.31E+04	7.95E+04	12.350	8.03E+03
3L75	8.33E+03	4.59E+04	8.84E+04	12.623	8.33E+03
(AC-20)					
10PAO	6.31E+03	3.73E+04	7.45E+04	10.686	6.31E+03
10PAR	8.44E+03	4.85E+04	8.99E+04	13.464	8.44E+03
10PO	9.37E+03	5.16E+04	9.18E+04	14.546	9.37E+03
10L35	1.38E+04	7.76E+04	1.30E+05	19.563	1.38E+04
(AC-20)					
12PAO	6.69E+03	3.83E+04	7.40E+04	11.051	6.69E+03
12PAR	8.70E+03	4.98E+04	9.13E+04	13.677	8.70E+03
12PO	9.52E+03	5.16E+04	9.14E+04	14.555	9.52E+03
12L35	7.81E+03	4.34E+04	7.98E+04	12.625	7.81E+03

WTMWT : weighted average molecular weight.
ZMWT : Z average molecular weight.
Z1MWT : Z+1 average molecular weight.
POLYIDX : polydisperse index.
HPVIS : calculated average viscosity.

Table 10. HP-GPC results - percent changes, 3 & 4-slice methods.

sample ID	LMS	MMS1	MMS2	SMS	LMSMMS1
(AC-5)					
4PAO	0.00	0.00	0.00	0.00	0.00
4PAR	43.35	5.47	-5.48	-2.91	10.55
4PO	74.83	8.28	-8.48	-7.47	17.21
4PM	10.06	8.00	-4.48	-1.16	8.28
4PC	-9.35	1.89	-0.25	0.16	0.38
4L35	20.39	8.47	-4.61	-6.37	10.07
4L75	39.48	11.58	-6.78	-11.11	15.32
(AC-5)					
5PAO	0.00	0.00	0.00	0.00	0.00
5PAR	54.60	6.85	-6.16	-5.36	12.97
5PO	91.55	10.86	-9.62	-11.41	21.20
5PM	-3.19	7.40	-1.93	-7.87	6.04
5L35	44.86	11.20	-6.26	-12.74	15.51
(AC-5)					
7PAO	0.00	0.00	0.00	0.00	0.00
7PAR	391.15	28.54	-12.10	-26.21	46.13
7PO	548.54	34.98	-16.37	-30.93	59.90
7L35	341.24	30.63	-11.43	-28.64	45.70
(AC-5)					
8PAO	0.00	0.00	0.00	0.00	0.00
8PAR	55.12	4.34	-5.45	-2.01	10.39
8PO	78.54	7.17	-7.59	-6.68	15.67
8L35	28.71	5.60	-3.96	-4.08	8.35
(AC-10)					
1PAO	0.00	0.00	0.00	0.00	0.00
1PAR	34.94	6.98	-4.46	-2.39	10.21
1PO	66.88	13.16	-7.49	-10.65	19.36
1PM	8.05	12.10	-5.28	-1.49	11.63
1L35	32.20	14.63	-6.91	-6.26	16.66
1L75	-9.21	10.55	-4.04	0.73	8.27
(AC-10)					
11PAO	0.00	0.00	0.00	0.00	0.00
11PAR	60.65	5.94	-6.02	-5.09	12.34
11PO	87.19	8.58	-8.62	-7.64	17.77
11L35	37.05	4.60	-4.58	-0.50	8.39

continued

sample ID	LMS	MMS1	MMS2	SMS	LMSMMS1
(AC-20)					
2PAO	0.00	0.00	0.00	0.00	0.00
2PAR	35.25	6.75	-6.00	-4.29	10.37
2PO	63.19	12.36	-10.39	-11.82	18.83
2PM	25.22	10.01	-7.09	-3.54	11.95
2PC	27.67	9.89	-7.21	-3.75	12.15
2LM	29.45	5.55	-6.29	6.81	8.58
2L35	31.27	7.49	-6.78	1.17	10.51
2L75	26.40	5.60	-6.01	6.27	8.25
(AC-20)					
3PAO	0.00	0.00	0.00	0.00	0.00
3PAR	48.60	5.21	-5.66	-4.77	10.93
3PO	79.91	8.93	-8.99	-11.11	18.28
3PM	3.92	6.53	-4.09	3.05	6.19
3PC	-3.00	5.35	-2.21	-1.78	4.25
3L35	29.01	8.62	-5.62	-6.36	11.31
3L75	34.24	10.07	-6.62	-7.38	13.25
(AC-20)					
10PAO	0.00	0.00	0.00	0.00	0.00
10PAR	59.50	6.05	-6.16	-5.36	12.48
10PO	86.50	8.23	-8.63	-8.16	17.65
10L35	186.78	10.15	-14.84	-17.83	31.41
(AC-20)					
12PAO	0.00	0.00	0.00	0.00	0.00
12PAR	51.07	4.12	-5.28	-4.60	10.12
12PO	73.08	6.81	-7.90	-7.32	15.28
12L35	29.05	3.70	-4.11	-0.07	6.94

Table 11. HP-GPC results - percent changes, 8-slice method.

sample ID	X1	X2	X3	X4	X5	X6	X7	X8
(AC-5)								
4PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4PAR	24.19	1.38	-4.33	-5.54	-5.81	-6.01	-4.68	-2.70
4PO	39.18	2.65	-6.57	-8.48	-9.57	-8.87	-7.97	-7.57
4PM	9.63	7.00	3.40	-4.27	-7.23	-7.65	-6.10	-0.52
4PC	-2.53	2.47	1.87	0.12	-1.41	-1.40	0.00	-0.05
4L35	17.18	5.72	0.37	-3.91	-5.87	-7.39	-7.46	-6.21
4L75	27.31	7.55	-0.13	-5.46	-8.63	-10.27	-10.78	-11.25
(AC-5)								
5PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5PAR	28.71	2.80	-4.02	-6.32	-6.99	-6.58	-6.61	-5.25
5PO	47.09	4.33	-6.19	-9.68	-10.82	-10.35	-10.91	-11.57
5PM	2.64	8.36	5.59	-1.39	-3.90	-5.22	-5.87	-8.29
5L35	28.60	7.51	-1.29	-5.69	-7.62	-8.35	-9.18	-13.45
(AC-5)								
7PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7PAR	119.28	16.01	1.00	-7.33	-12.15	-19.16	-25.73	-26.05
7PO	161.22	18.25	-2.04	-11.97	-16.68	-23.67	-29.96	-30.87
7L35	111.98	18.68	3.49	-6.38	-11.32	-19.41	-27.03	-28.63
(AC-5)								
8PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8PAR	25.59	0.68	-4.71	-5.64	-6.13	-5.38	-4.21	-1.86
8PO	37.96	1.44	-6.11	-7.87	-8.26	-7.83	-7.11	-6.79
8L35	16.34	3.40	-1.09	-3.97	-4.99	-4.89	-4.75	-4.13
(AC-10)								
1PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1PAR	19.15	5.28	-2.12	-4.82	-4.47	-5.26	-4.85	-2.11
1PO	37.69	9.10	-3.15	-8.06	-7.55	-8.41	-11.39	-10.13
1PM	11.33	12.37	3.86	-6.48	-8.17	-8.36	-4.66	-1.31
1L35	24.61	13.30	1.15	-7.29	-8.87	-10.18	-9.23	-5.84
1L75	4.93	11.43	2.93	-5.61	-6.33	-5.81	-3.30	1.19
(AC-10)								
11PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11PAR	28.45	2.06	-4.25	-5.93	-7.00	-6.21	-6.13	-4.97
11PO	41.20	2.88	-6.21	-8.76	-9.68	-8.92	-8.85	-7.47
11L35	18.51	2.38	-2.92	-4.04	-6.56	-4.64	-4.63	0.12

continued

sample ID	X1	X2	X3	X4	X5	X6	X7	X8
(AC-20)								
2PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2PAR	21.22	3.74	-3.39	-6.64	-6.62	-6.48	-7.00	-3.85
2PO	38.08	7.20	-6.17	-11.39	-11.32	-10.51	-14.02	-11.03
2PM	19.88	7.50	-1.80	-7.47	-9.00	-8.85	-9.25	-2.60
2PC	22.70	6.08	-2.42	-8.12	-8.81	-9.11	-8.40	-3.01
2LM	19.43	2.25	-6.32	-9.72	-7.09	-3.17	1.94	7.30
2L35	22.45	3.68	-5.57	-9.98	-7.98	-4.46	-0.85	1.30
2L75	19.02	2.05	-6.33	-9.67	-6.50	-2.80	2.30	6.66
(AC-20)								
3PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3PAR	24.65	2.02	-4.48	-5.42	-5.63	-6.67	-6.11	-4.65
3PO	40.71	3.63	-7.13	-9.12	-9.26	-8.82	-11.90	-10.55
3PM	5.04	6.77	3.09	-4.51	-6.96	-6.41	-4.80	4.23
3PC	0.78	6.16	4.63	-2.40	-4.96	-4.54	-3.27	-1.73
3L35	20.07	5.87	-1.15	-4.70	-7.08	-8.03	-8.31	-6.00
3L75	22.89	7.35	-0.56	-5.46	-8.72	-9.86	-10.04	-7.15
(AC-20)								
10PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10PAR	28.94	1.82	-4.04	-6.44	-7.17	-6.62	-5.88	-5.29
10PO	41.98	1.89	-6.28	-8.99	-9.43	-9.22	-8.60	-8.09
10L35	76.75	1.54	-10.42	-15.07	-16.37	-16.10	-16.00	-18.26
(AC-20)								
12PAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12PAR	23.86	0.77	-4.31	-5.10	-5.57	-5.66	-5.26	-4.53
12PO	35.46	1.69	-6.36	-7.62	-8.44	-8.48	-7.95	-7.22
12L35	15.55	1.22	-2.60	-4.58	-5.10	-4.56	-2.55	0.23

Table 12. Results of regression analyses - Task 1 asphalts.

Property	4-slice(ISU)	3-slice(MSU)	8-slice(Purdue)
	Coefficient of Determination, R-Square (n=24)		
	Rheological properties		
Log(Sp.Gr.)	0.245	0.244	0.652 **
Log(P25)	0.420 *	0.205	0.652 **
Log(P5)	0.275	0.174	0.473
Log(VIS60)	0.553 **	0.320 *	0.793 **
Log(VIS135)	0.618 **	0.357 *	0.798 **
Log(SP)	0.423 *	0.236	0.730 **
	Temperature susceptibility		
CN	0.408 *	0.349 *	0.740 **
PI	0.359	0.359 *	0.667 **
VTS	0.109	0.097	0.590 *
PVN60	0.441 *	0.398 *	0.597 *
PVN135	0.260	0.196	0.318
	Low-temperature cracking properties		
CT	0.250	0.249	0.429
TES	0.398 *	0.206	0.568
Log(S23)	0.370	0.165	0.531
Log(S29)	0.276	0.112	0.436
	Thermal properties		
Tg	0.451 *	0.313	0.451
ENTHP	0.544 **	0.415 *	0.757 **

Note:
Sp.Gr.= specific gravity; P25= penetration @ 25°C,100g,5sec; P5= penetration @ 5°C,100g,5sec; VIS60= viscosity @ 60°C; VIS135= viscosity @ 135°C; SP= R&B softening point; CN= class number; PI= penetration index; VTS= viscosity-temperature susceptibility; PVN= penetration-viscosity number @ 60°C; PVN135= penetration-viscosity number @ 135°C; CT= cracking temperature; TES= temperature of equivalent stiffness @ 20 ksi,10000sec; S23= stiffness @ -23°C,10000sec; S29= stiffness @-29°C,20000sec; Tg= glass transition temperature; ENTHP= enthalpy change

** significant at 1 % level * significant at 5 % level

Table 13a. Results of regression analyses - all field samples (n = 53).

	LMS+MMS1		4-SLICE		MW(W+P)		MW(Z+P)		3-SLICE		8-SLICE	
	P-value	R**2	P-value	R**2	P-value	R**2	P-value	R**2	P-value	R**2	P-value	R**2
TG	0.5403	0.007	0.1183	0.139	0.7951	0.009	0.7413	0.012	0.4725	0.050	0.0122	0.341
CT	0.5048	0.009	0.0011	0.311	0.0434	0.118	0.0883	0.093	0.0072	0.216	0.0001	0.498
TES	0.0001	0.313	0.0001	0.433	0.0001	0.347	0.0006	0.255	0.0001	0.362	0.0001	0.539
S23	0.0001	0.279	0.0001	0.532	0.0001	0.377	0.0072	0.179	0.0001	0.458	0.0001	0.604
S29	0.0001	0.274	0.0001	0.567	0.0001	0.390	0.0031	0.207	0.0001	0.497	0.0001	0.619
P5	0.0001	0.281	0.0001	0.497	0.0001	0.381	0.0078	0.177	0.0001	0.429	0.0001	0.610
P25	0.0001	0.435	0.0001	0.504	0.0001	0.422	0.0008	0.249	0.0001	0.488	0.0001	0.593
P4	0.0001	0.335	0.0001	0.485	0.0001	0.390	0.0049	0.192	0.0001	0.446	0.0001	0.594
PR	0.0001	0.379	0.0001	0.400	0.0001	0.347	0.0009	0.245	0.0001	0.397	0.0001	0.559
SP	0.0001	0.433	0.0001	0.466	0.0001	0.464	0.0031	0.207	0.0001	0.464	0.0001	0.617
PI	0.0724	0.062	0.1216	0.138	0.2855	0.049	0.5929	0.021	0.2659	0.077	0.0133	0.338
VIS25	0.0001	0.328	0.0001	0.401	0.0001	0.417	0.0173	0.150	0.0001	0.382	0.0001	0.583
CF	0.0001	0.325	0.0001	0.496	0.0001	0.506	0.0101	0.168	0.0001	0.401	0.0001	0.567
SI	0.0001	0.333	0.0001	0.474	0.0001	0.525	0.0098	0.169	0.0001	0.407	0.0001	0.555
VIS60	0.0004	0.222	0.0012	0.307	0.0001	0.403	0.0553	0.109	0.0004	0.305	0.0010	0.427
VIS135	0.0001	0.417	0.0001	0.545	0.0001	0.647	0.0004	0.272	0.0001	0.532	0.0001	0.634
CN	0.0399	0.080	0.2983	0.095	0.0315	0.129	0.4728	0.030	0.1895	0.092	0.0788	0.260
VTS	0.5525	0.007	0.6789	0.046	0.6145	0.019	0.4946	0.028	0.9388	0.008	0.0228	0.316
PVN60	0.0267	0.093	0.0581	0.170	0.0023	0.215	0.2424	0.055	0.0993	0.119	0.0449	0.287
PVN135	0.1505	0.040	0.0070	0.250	0.0081	0.175	0.0450	0.117	0.3166	0.069	0.0002	0.481
LOG(TG)	0.5379	0.007	0.1208	0.138	0.7948	0.009	0.7387	0.012	0.4716	0.050	0.0126	0.340
LOG(CT)	0.5044	0.009	0.0012	0.310	0.0437	0.118	0.0877	0.093	0.0074	0.215	0.0001	0.498
LOG(TES)	0.0001	0.309	0.0001	0.426	0.0001	0.342	0.0007	0.252	0.0001	0.356	0.0001	0.532
LOG(S23)	0.0001	0.359	0.0001	0.509	0.0001	0.393	0.0016	0.227	0.0001	0.460	0.0001	0.600
LOG(S29)	0.0001	0.318	0.0001	0.481	0.0001	0.362	0.0035	0.203	0.0001	0.425	0.0001	0.579
LOG(P5)	0.0001	0.295	0.0001	0.539	0.0001	0.419	0.0051	0.190	0.0001	0.471	0.0001	0.650
LOG(P25)	0.0001	0.442	0.0001	0.525	0.0001	0.481	0.0012	0.236	0.0001	0.505	0.0001	0.646
LOG(P4)	0.0001	0.347	0.0001	0.541	0.0001	0.448	0.0035	0.203	0.0001	0.497	0.0001	0.657
LOG(PR)	0.0001	0.387	0.0001	0.417	0.0001	0.346	0.0007	0.254	0.0001	0.412	0.0001	0.588
LOG(SP)	0.0001	0.448	0.0001	0.481	0.0001	0.464	0.0022	0.217	0.0001	0.479	0.0001	0.623
LOG(VIS25)	0.0001	0.420	0.0001	0.462	0.0001	0.450	0.0026	0.212	0.0001	0.458	0.0001	0.599
LOG(CF)	0.0001	0.299	0.0001	0.494	0.0001	0.511	0.0087	0.173	0.0001	0.386	0.0001	0.548
LOG(SI)	0.0001	0.365	0.0001	0.443	0.0001	0.423	0.0165	0.151	0.0001	0.408	0.0001	0.551
LOG(VIS60)	0.0001	0.397	0.0001	0.466	0.0001	0.494	0.0044	0.195	0.0001	0.466	0.0001	0.582
LOG(VIS135)	0.0001	0.469	0.0001	0.579	0.0001	0.601	0.0005	0.264	0.0001	0.569	0.0001	0.675
LOG(VTS)	0.5912	0.006	0.6694	0.047	0.6605	0.016	0.5738	0.022	0.9524	0.007	0.0339	0.299

Table 13b. Results of regression analyses - original asphalts (n = 10).

	LMS+MMS1		4-SLICE		MW(W+P)		MW(Z+P)		3-SLICE		8-SLICE*		
	P-value	R**2	P-value	R**2	P-value	R**2	P-value	R**2	P-value	R**2	P-value	R**2	**
TG	0.0080	0.605	0.0448	0.815	0.0682	0.536	0.2601	0.319	0.0771	0.655	0.0043	0.661	X2
CT	0.8057	0.008	0.3538	0.529	0.2248	0.347	0.3121	0.283	0.2598	0.464	0.0554	0.386	X4
TES	0.2609	0.155	0.0414	0.821	0.0166	0.690	0.1041	0.476	0.1124	0.606	0.0028	0.890	X3,X4,X5
S23	0.1115	0.286	0.0291	0.846	0.0001	0.943	0.0019	0.832	0.0484	0.707	0.0001	0.921	X3,X6
S29	0.1214	0.273	0.0273	0.850	0.0001	0.944	0.0012	0.855	0.0488	0.707	0.0001	0.933	X3,X6
P5	0.3298	0.119	0.1130	0.723	0.1113	0.466	0.2336	0.340	0.0964	0.627	0.0557	0.385	X4
P25	0.1416	0.249	0.0472	0.811	0.0720	0.528	0.1722	0.395	0.0355	0.737	0.0188	0.679	X5,X8
P4	0.1771	0.215	0.0280	0.848	0.0370	0.610	0.1341	0.437	0.0539	0.696	0.0015	0.910	X2,X3,X5
PR	0.8964	0.002	0.0493	0.807	0.2327	0.341	0.2545	0.324	0.1163	0.601	0.8274	0.781	ALL
SP	0.1196	0.275	0.1056	0.732	0.1135	0.463	0.1763	0.391	0.0489	0.706	0.0213	0.667	X5,X8
PI	0.6604	0.025	0.2787	0.581	0.0479	0.580	0.1818	0.386	0.5195	0.296	0.0967	0.307	X4
VIS25	0.1176	0.278	0.0119	0.894	0.0001	0.963	0.0017	0.837	0.0415	0.723	0.0001	0.953	X3,X6
CF	0.2759	0.146	0.1630	0.674	0.2362	0.338	0.0944	0.491	0.0661	0.673	0.0389	0.604	X1,X4
SI	0.3788	0.098	0.3276	0.547	0.1983	0.370	0.0157	0.695	0.1663	0.546	0.0060	0.857	X3,X4,X5
VIS60	0.0812	0.332	0.0529	0.801	0.0038	0.796	0.0779	0.518	0.1057	0.614	0.0031	0.685	X3
VIS135	0.0658	0.362	0.0039	0.933	0.0001	0.955	0.0154	0.696	0.0763	0.656	0.0001	0.939	X3,X6
CN	0.2770	0.145	0.4438	0.471	0.2840	0.302	0.0655	0.541	0.2517	0.470	0.0583	0.378	X3
VTS	0.1462	0.245	0.3769	0.514	0.1342	0.437	0.2344	0.339	0.4884	0.314	0.0200	0.512	X3
PVN60	0.3983	0.090	0.0225	0.861	0.5091	0.175	0.1116	0.466	0.0784	0.653	0.0129	0.815	X1,X2,X4
PVN135	0.3493	0.110	0.2083	0.635	0.4251	0.217	0.8393	0.049	0.7381	0.177	0.0610	0.550	X1,X2
VISR	0.9198	0.001	0.6692	0.331	0.2402	0.335	0.0832	0.509	0.4589	0.331	0.0544	0.388	X4
LOG(TG)	0.0077	0.609	0.0432	0.818	0.0667	0.539	0.2556	0.323	0.0747	0.659	0.0041	0.664	X2
LOG(CT)	0.8085	0.008	0.3542	0.529	0.2236	0.348	0.3118	0.283	0.2619	0.462	0.0555	0.385	X4
LOG(TES)	0.2696	0.150	0.0433	0.818	0.0186	0.680	0.1117	0.465	0.1173	0.600	0.0028	0.890	X3,X4,X5
LOG(S23)	0.1463	0.244	0.0334	0.836	0.0221	0.663	0.0915	0.495	0.0451	0.714	0.0037	0.878	X3,X4,X5
LOG(S29)	0.1601	0.231	0.0207	0.866	0.0149	0.699	0.0712	0.530	0.0437	0.718	0.0022	0.899	X3,X4,X5
LOG(P5)	0.2843	0.141	0.1054	0.732	0.0836	0.508	0.1671	0.400	0.0755	0.658	0.0398	0.602	X4,X8
LOG(P25)	0.1260	0.267	0.0358	0.832	0.0301	0.632	0.0909	0.496	0.0320	0.747	0.0024	0.821	X2,X5
LOG(P4)	0.1348	0.257	0.0116	0.895	0.0057	0.771	0.0366	0.611	0.0331	0.744	0.0002	0.919	X2,X5
LOG(PR)	0.9530	0.000	0.0435	0.817	0.1991	0.369	0.2252	0.347	0.1202	0.596	0.8006	0.803	ALL
LOG(SP)	0.1166	0.279	0.1053	0.732	0.1194	0.455	0.1826	0.385	0.0471	0.710	0.0220	0.664	X5,X8
LOG(VIS25)	0.1830	0.210	0.0261	0.853	0.0115	0.721	0.0725	0.527	0.0675	0.671	0.0041	0.875	X3,X4,X5
LOG(CF)	0.2753	0.146	0.1606	0.676	0.2306	0.342	0.0898	0.498	0.0650	0.676	0.0366	0.611	X1,X4
LOG(SI)	0.4482	0.074	0.4544	0.464	0.3582	0.254	0.0450	0.588	0.2613	0.463	0.0306	0.462	X4
LOG(VIS60)	0.1315	0.261	0.0558	0.797	0.0286	0.638	0.1800	0.382	0.1091	0.610	0.0154	0.540	X3
LOG(VIS135)	0.0626	0.369	0.0032	0.938	0.0016	0.842	0.0610	0.550	0.0761	0.657	0.0007	0.784	X3
LOG(VTS)	0.1486	0.242	0.3707	0.518	0.1291	0.443	0.2282	0.344	0.4888	0.313	0.0193	0.516	X3
LOG(VISR)	0.8081	0.008	0.6071	0.370	0.1553	0.413	0.0470	0.582	0.4012	0.366	0.0379	0.436	X4

* Stepwise linear regression used.
** Selected independent variables in the regression analyses.

LIST OF FIGURES

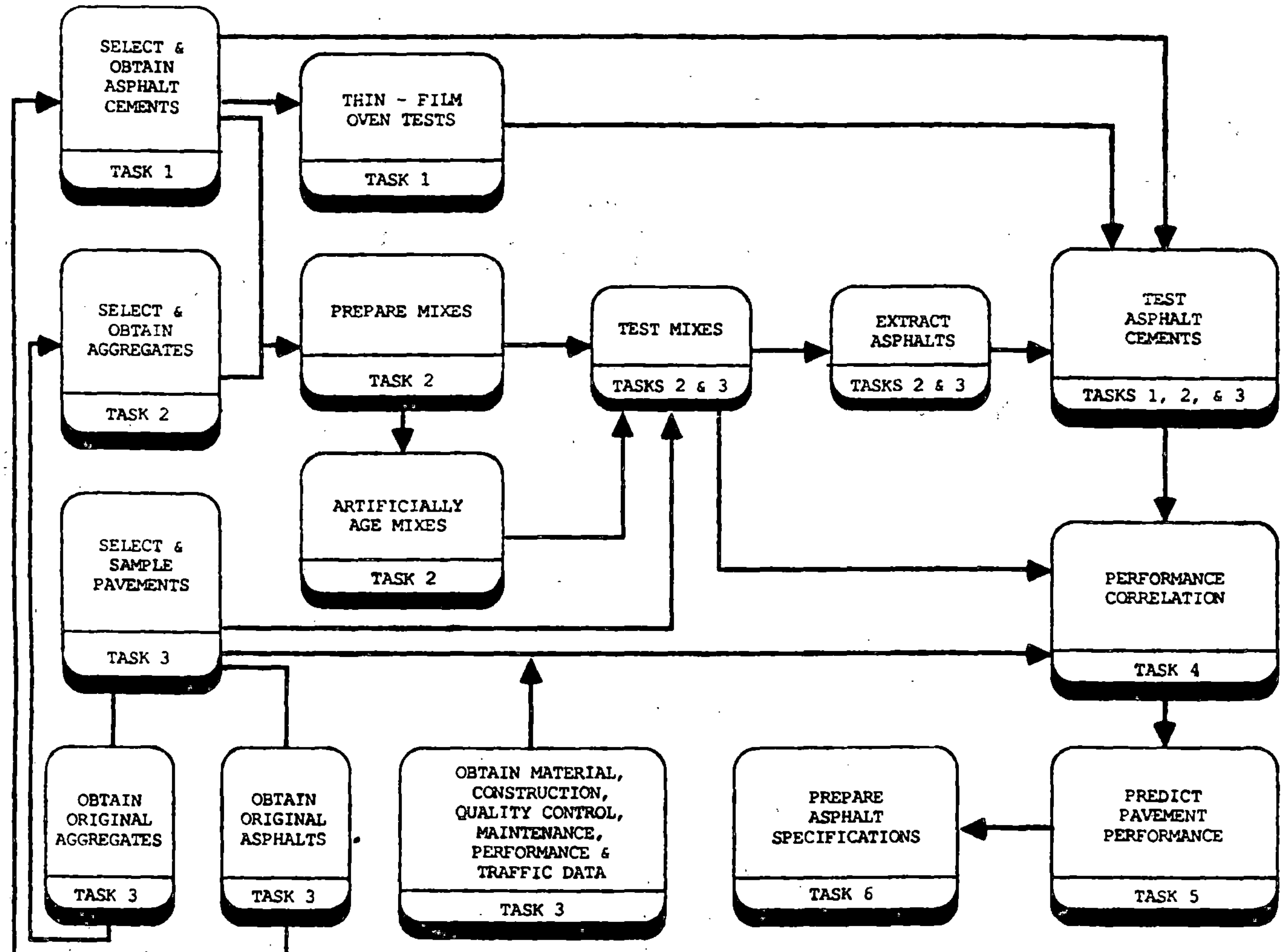


FIGURE 1. SUMMARY OF PROPOSED RESEARCH

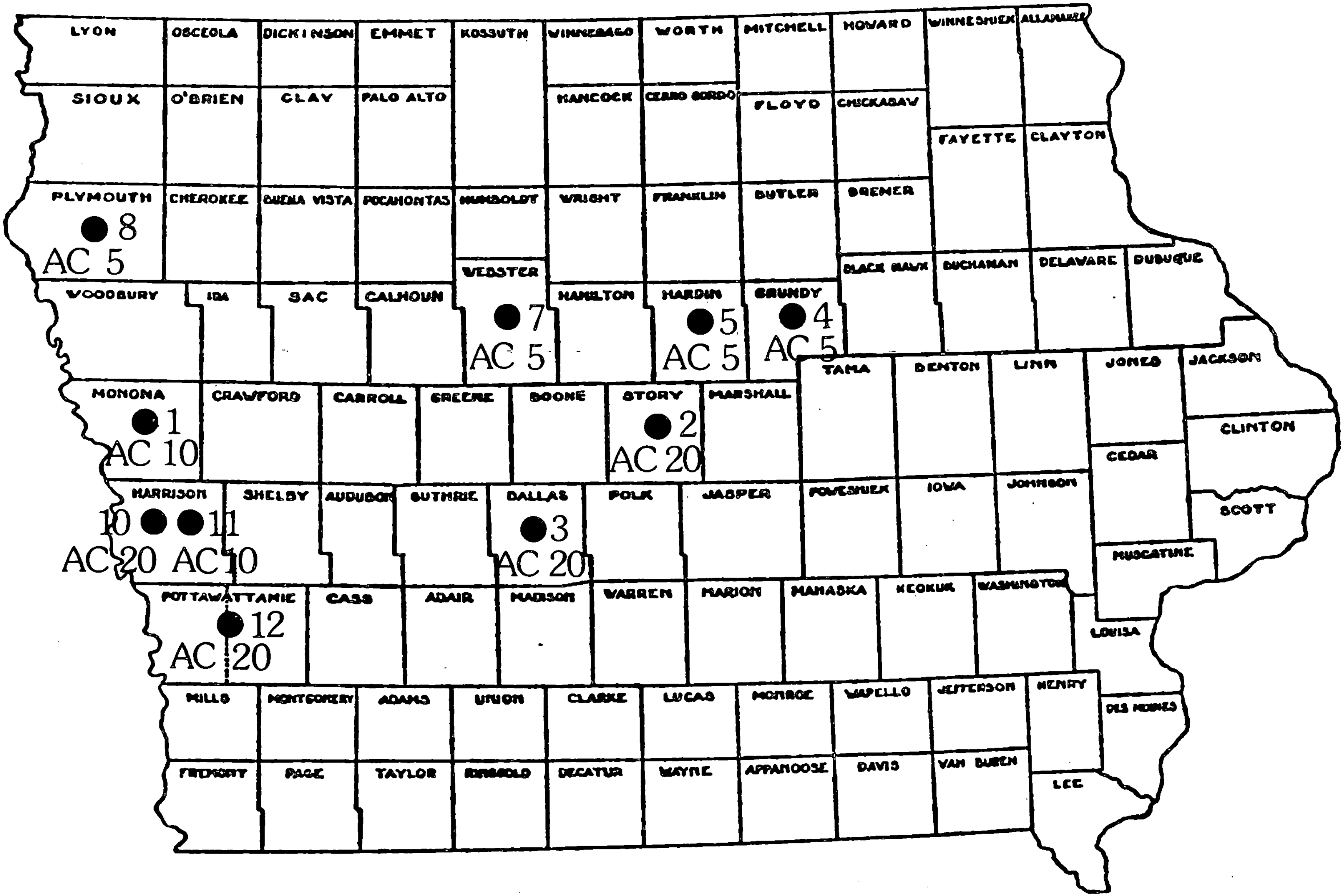


Figure 2. Pavement project locations.

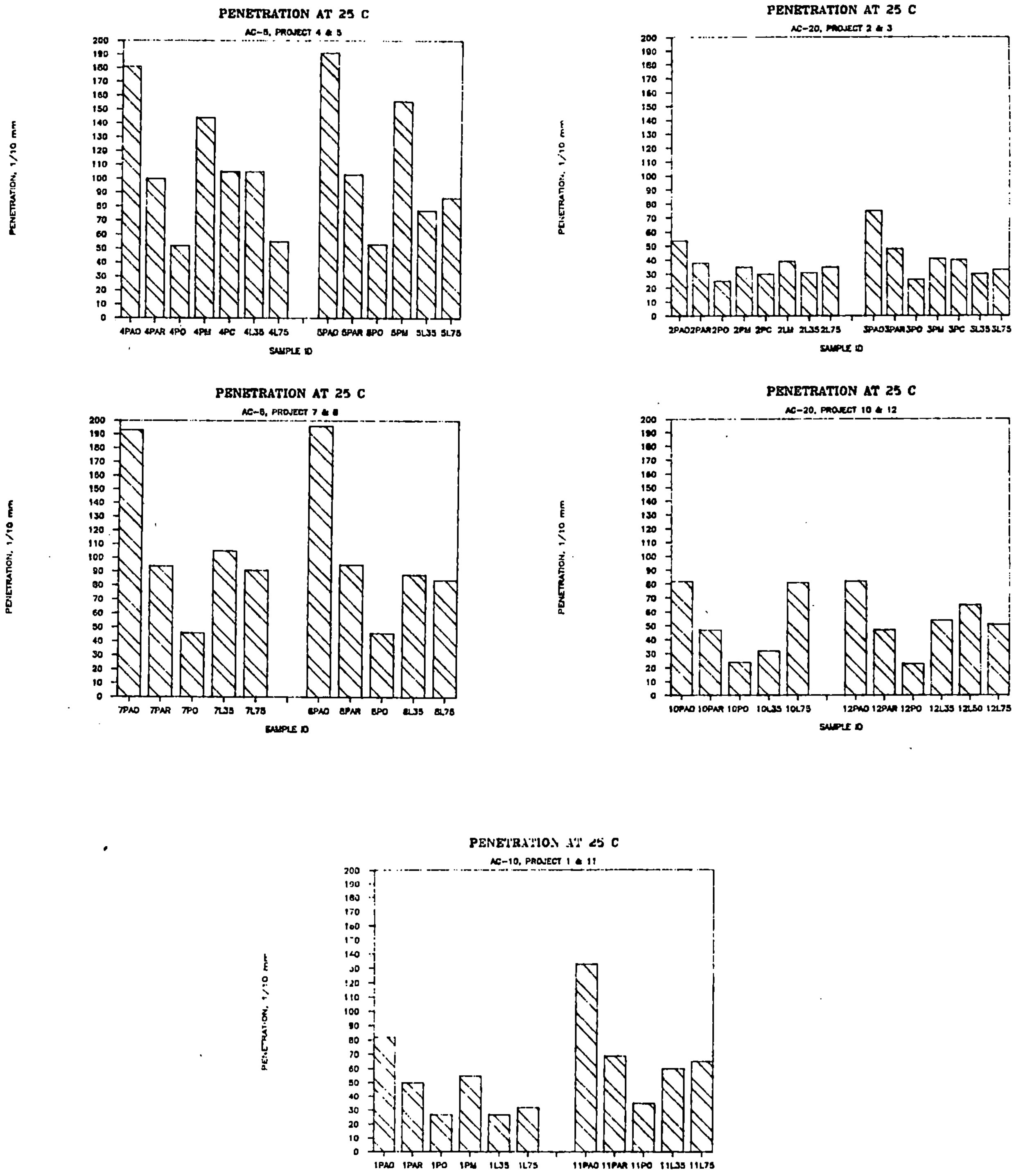


Figure 3. Penetration at 25°C.

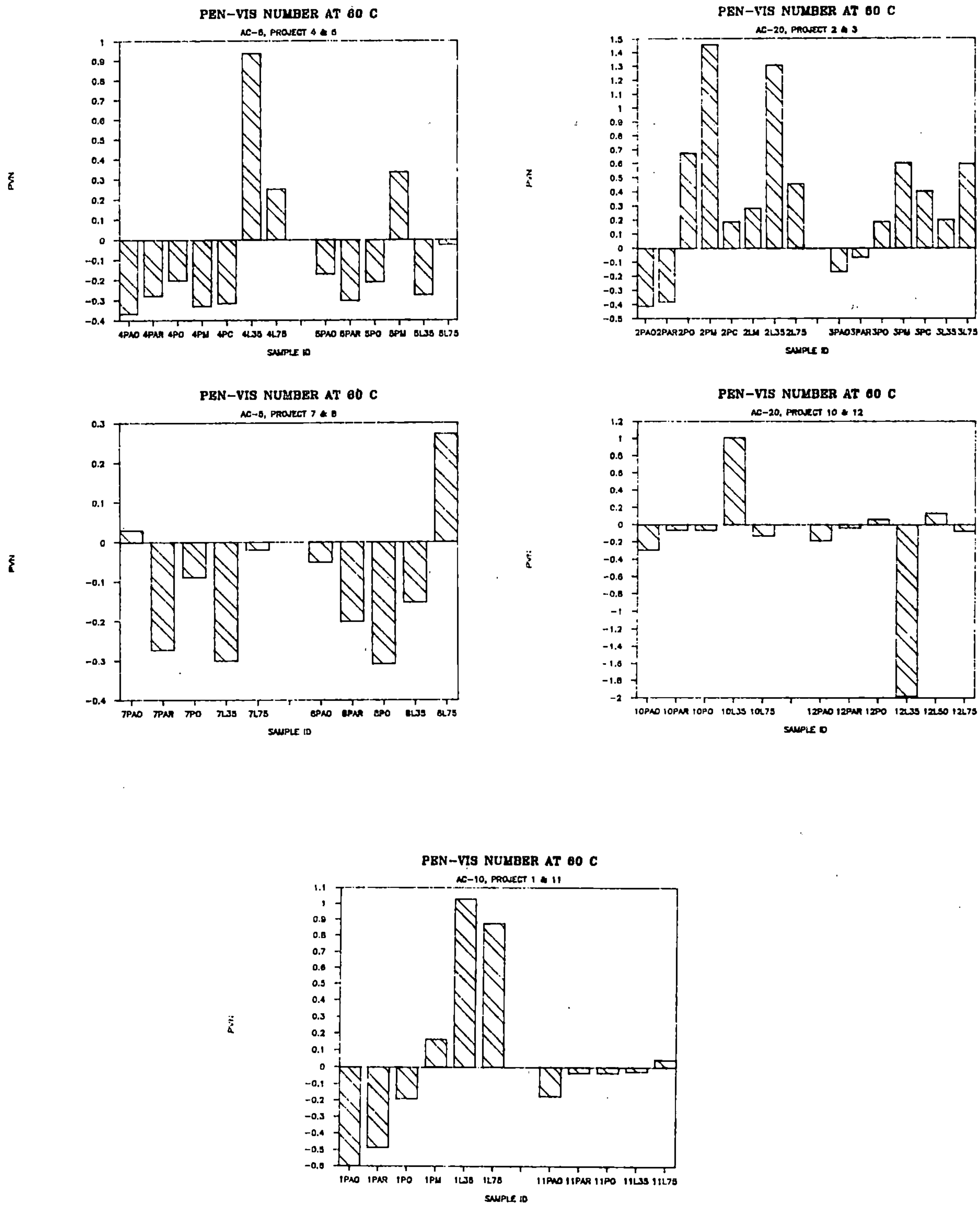
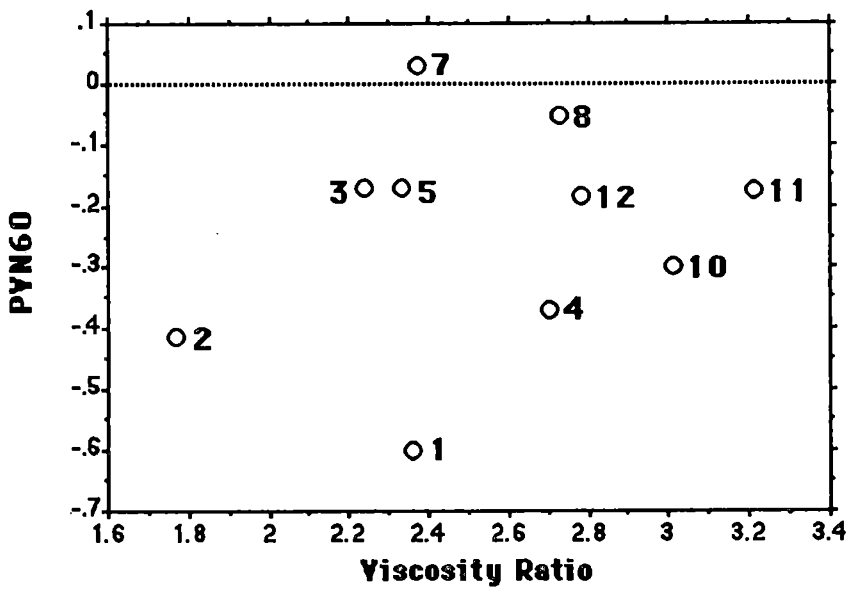


Figure 4. PVN at 60°C.



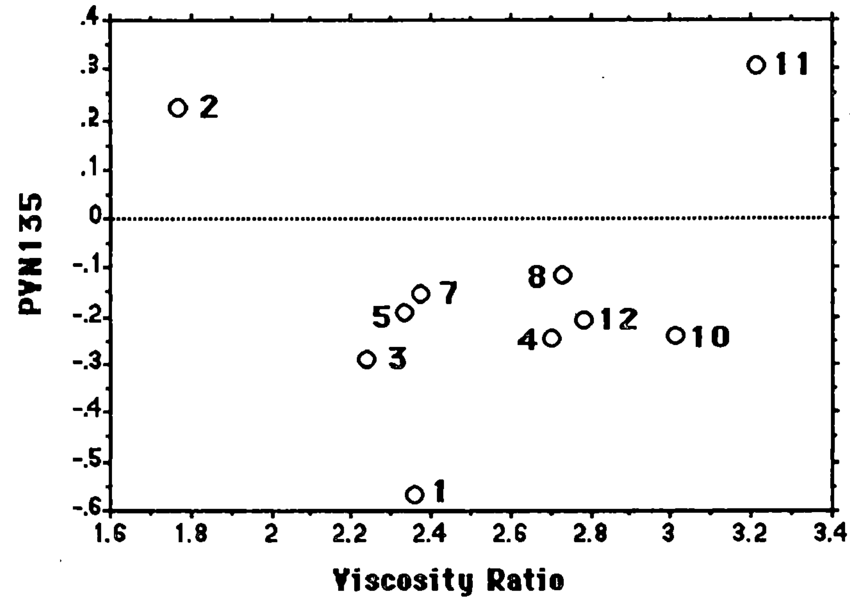


Figure 5. PVN vs viscosity ratio at 60°C.

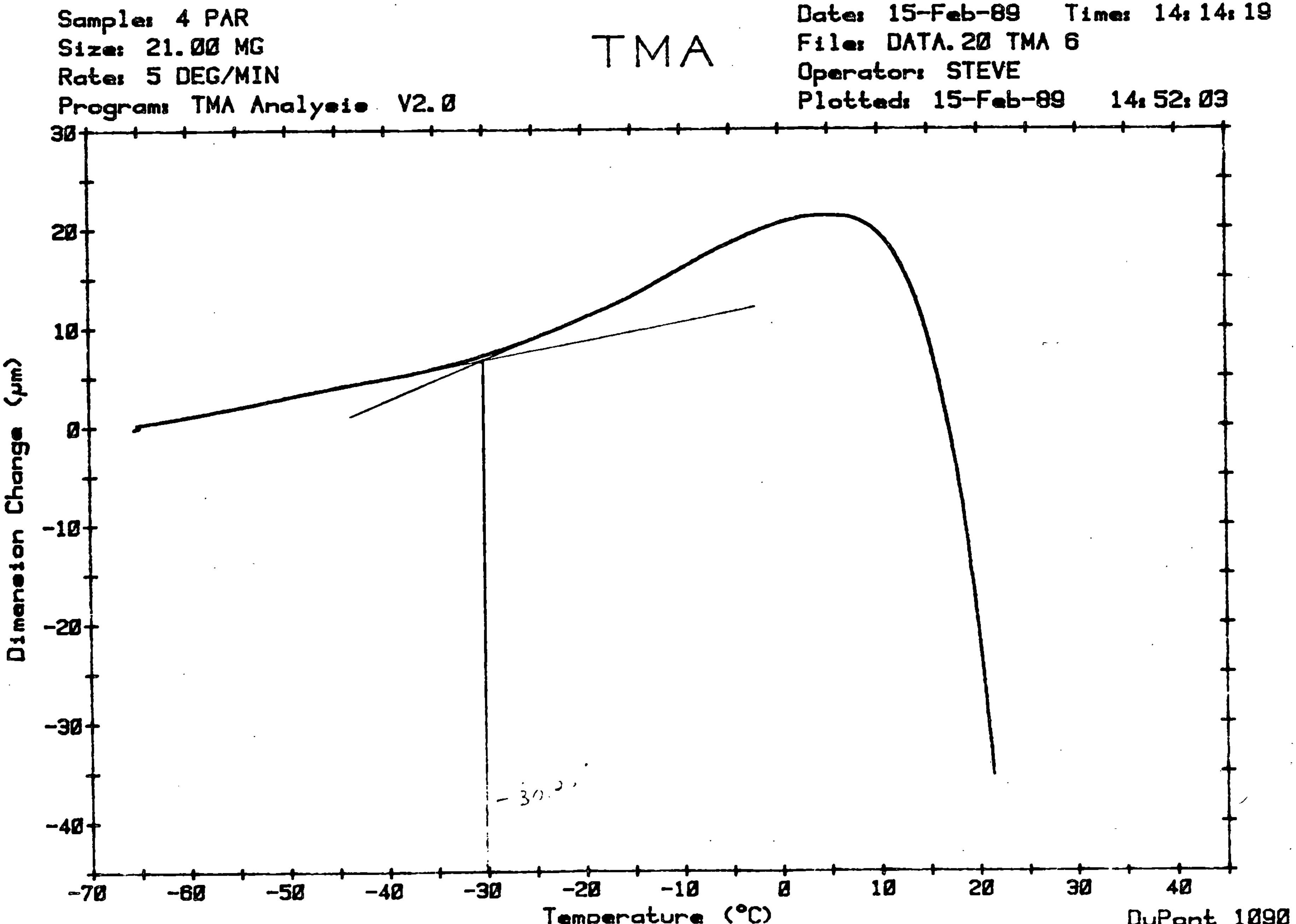


Figure 6. Typical TMA thermogram.

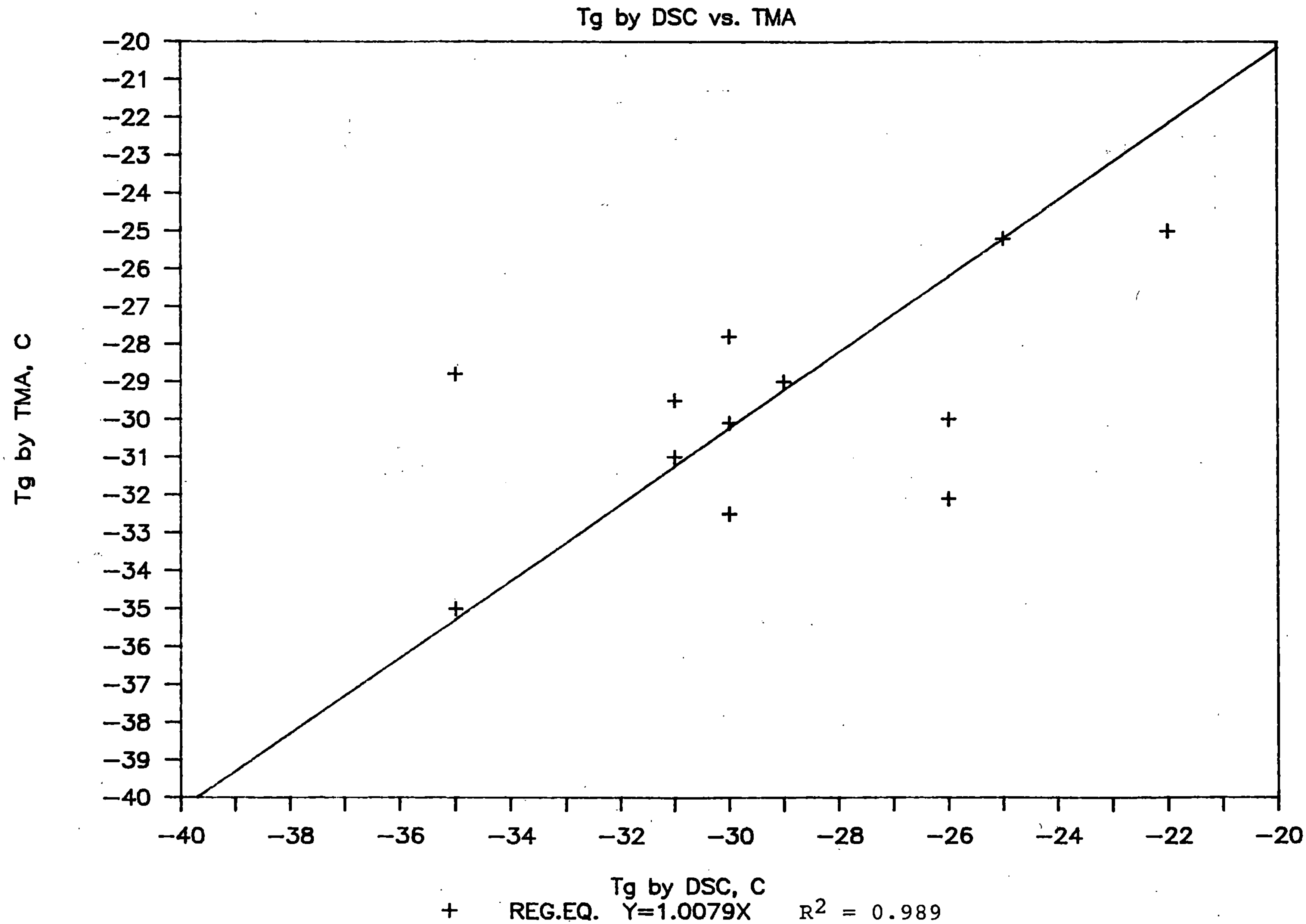


Figure 7. Glass transition temperature, TMA vs DSC methods.

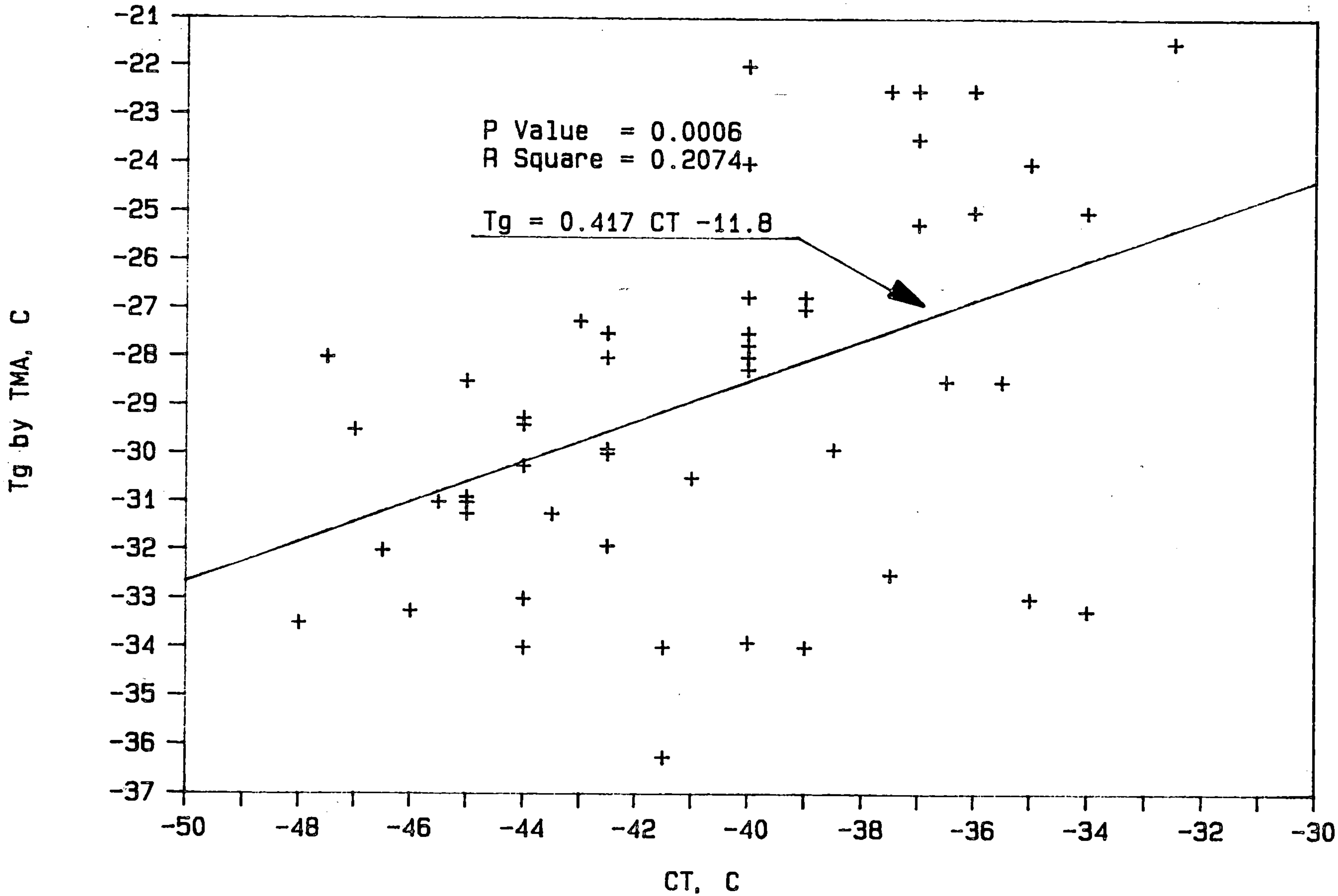


Figure 8. Glass transition temperature vs cracking temperature.

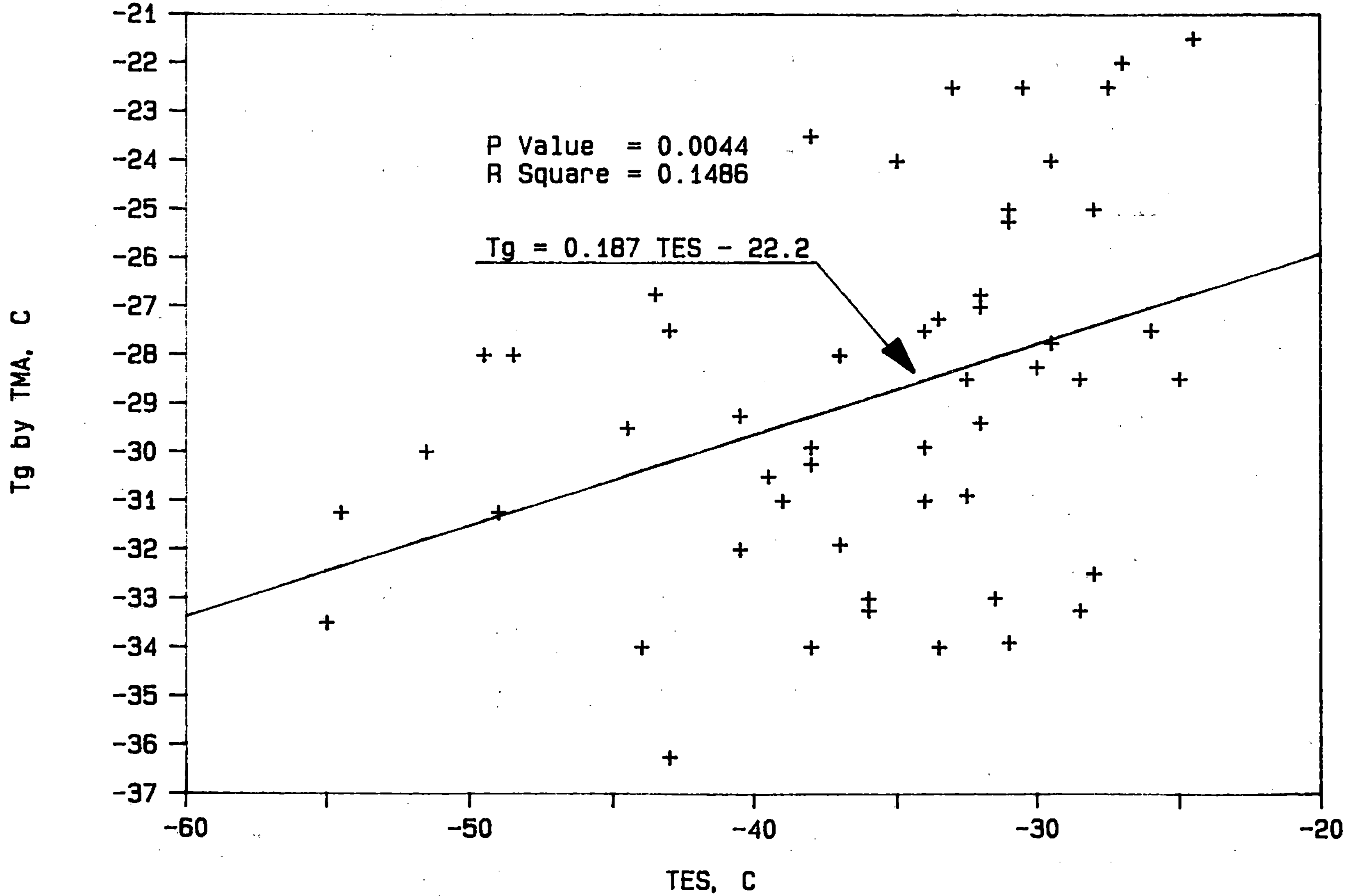


Figure 9. Glass transition temperature vs temperature of equivalent stiffness.

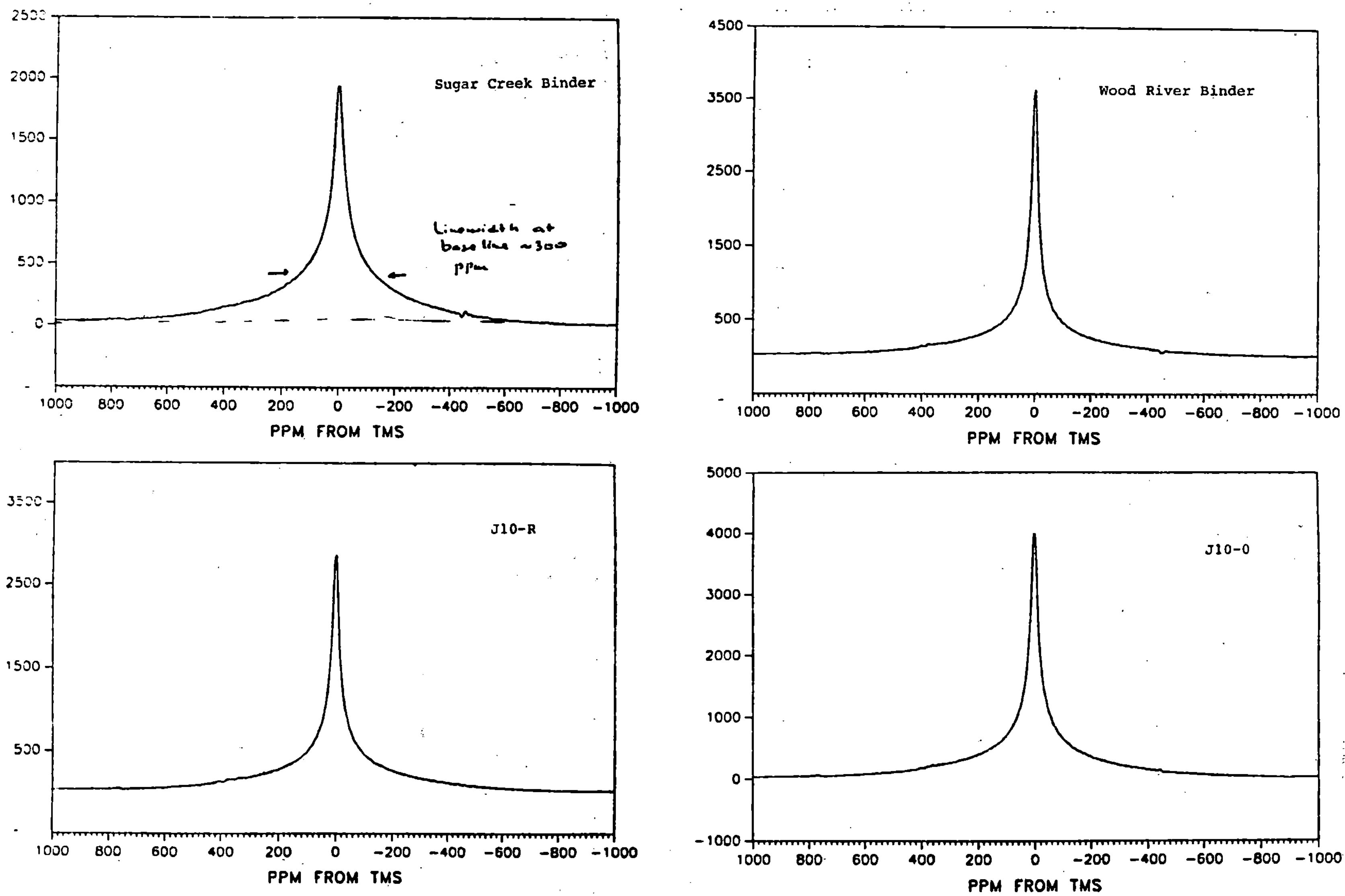


Figure 10. Carbon 13 NMR spectra.

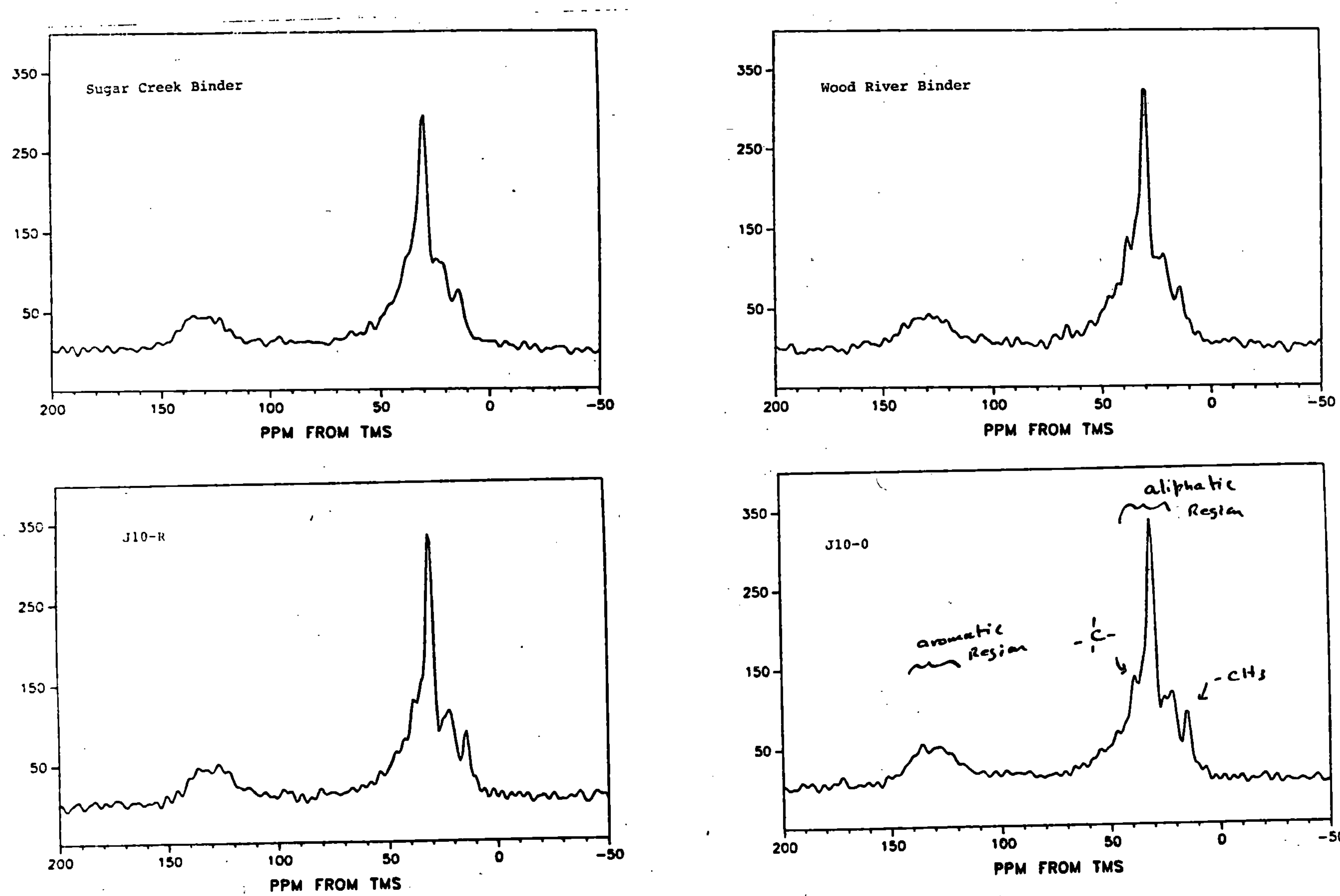


Figure 11. Proton NMR spectra.

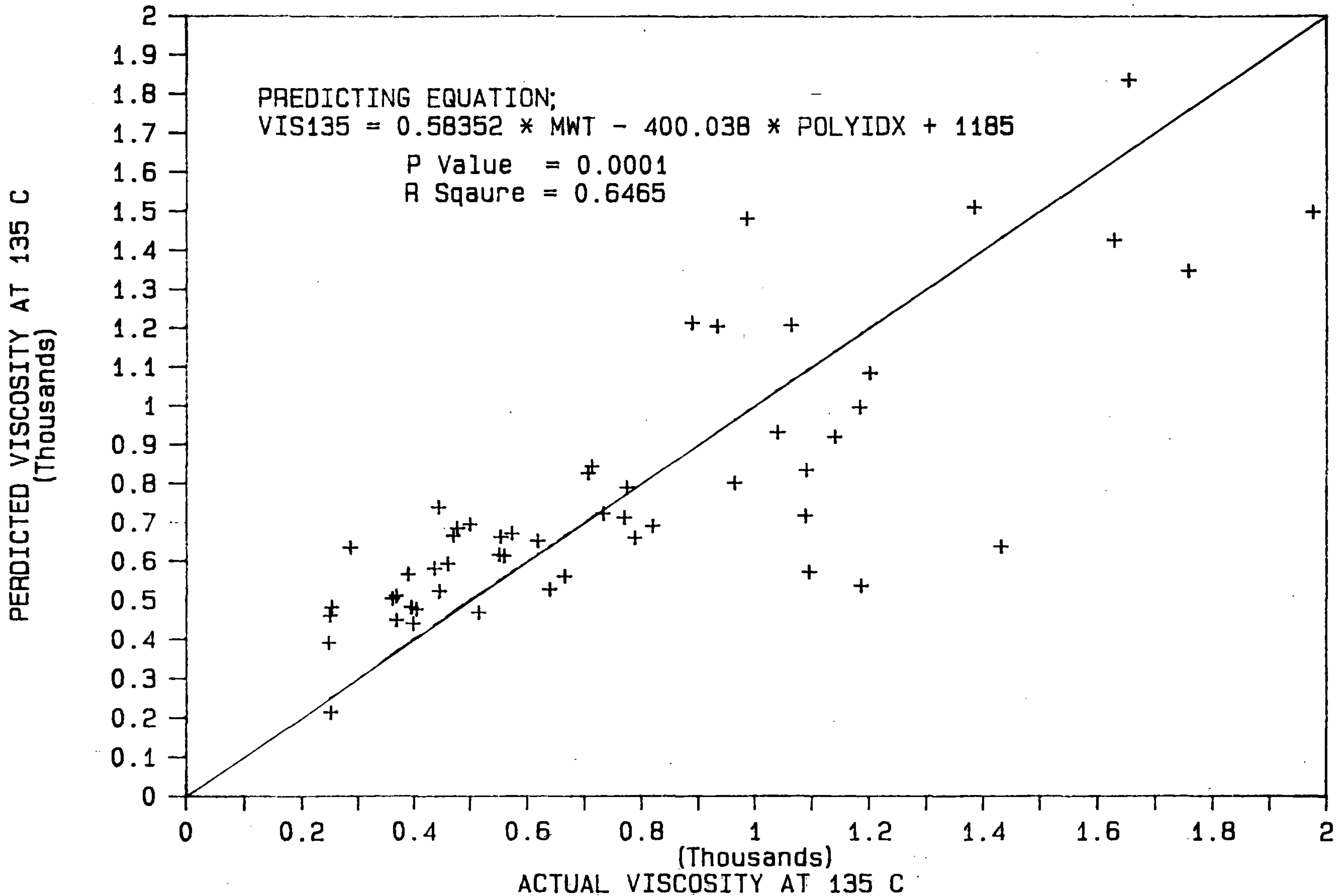
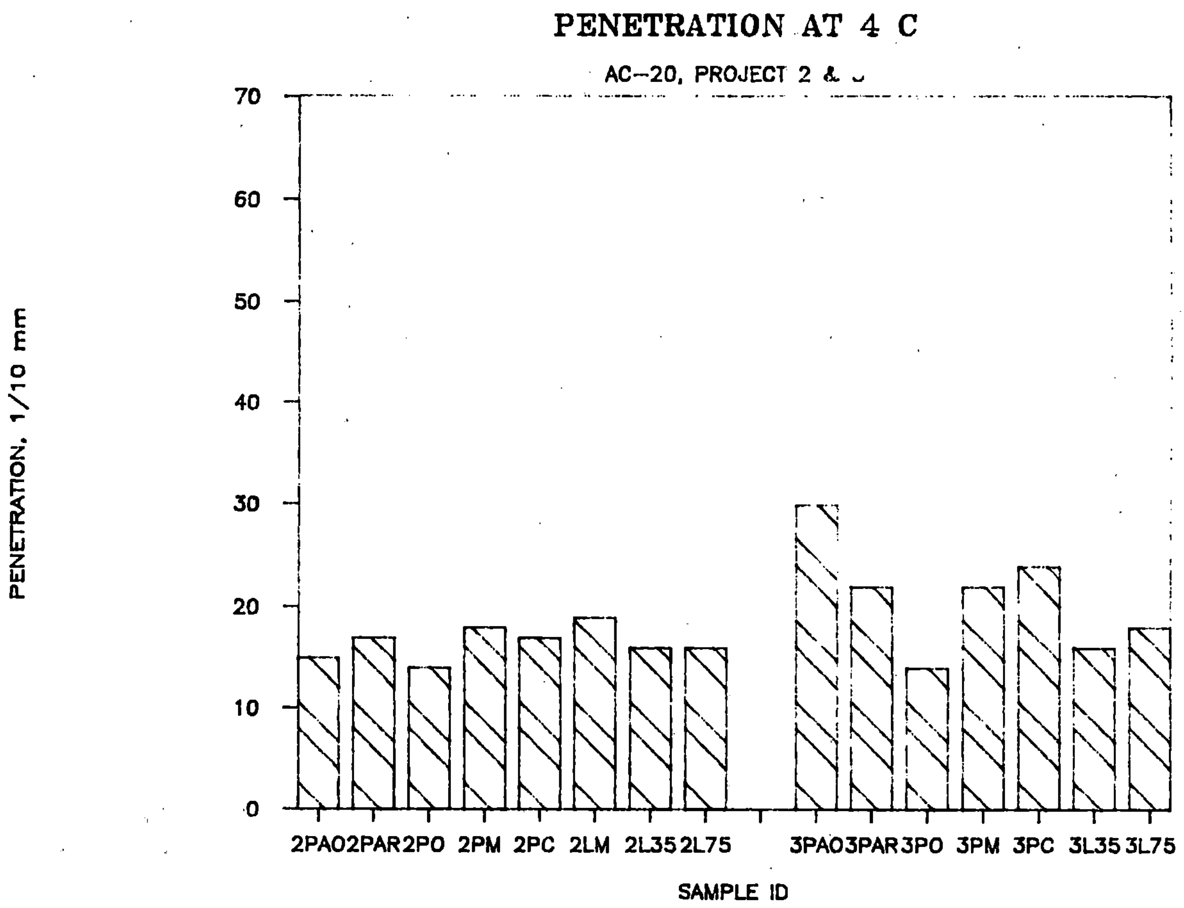
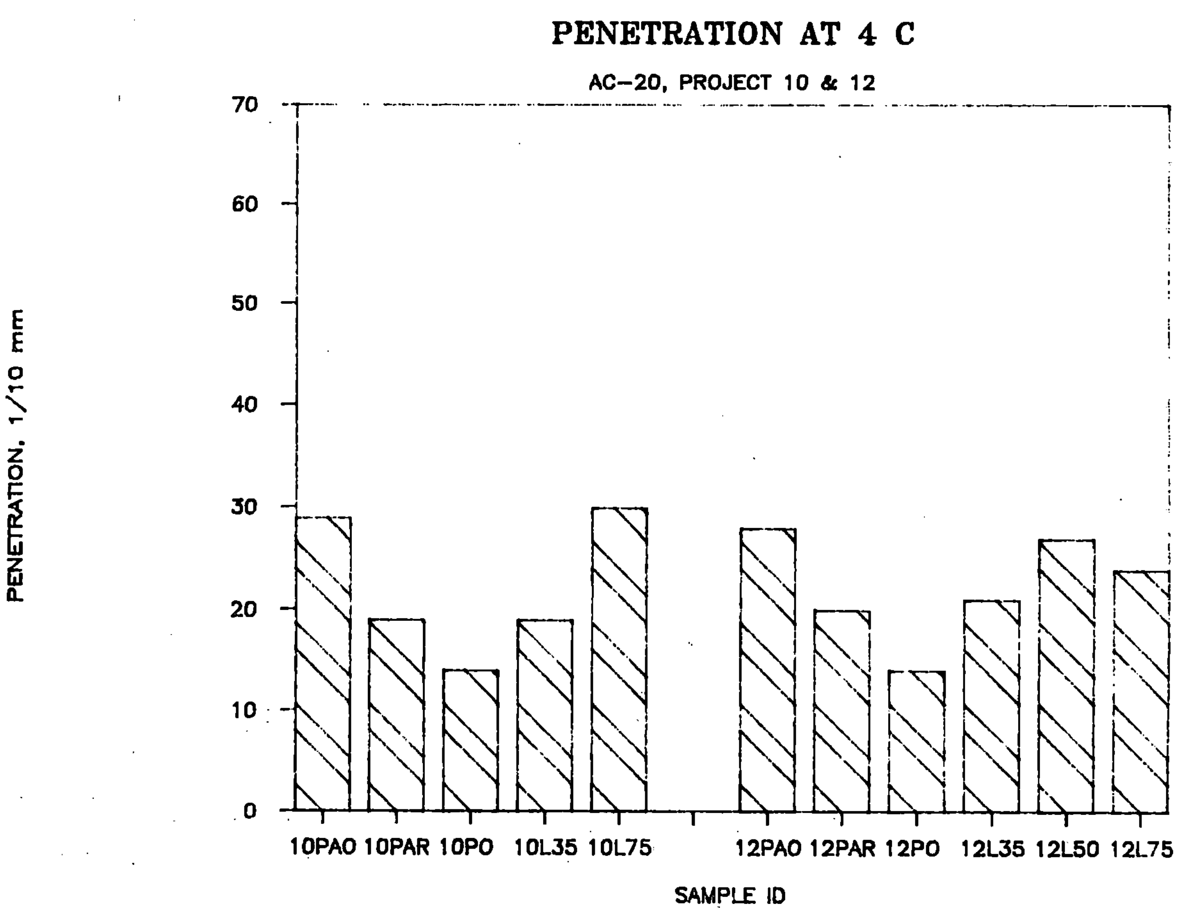


Figure 12. Actual kinematic viscosity (VIS135) vs predicted viscosity from regression analysis.

APPENDIX I

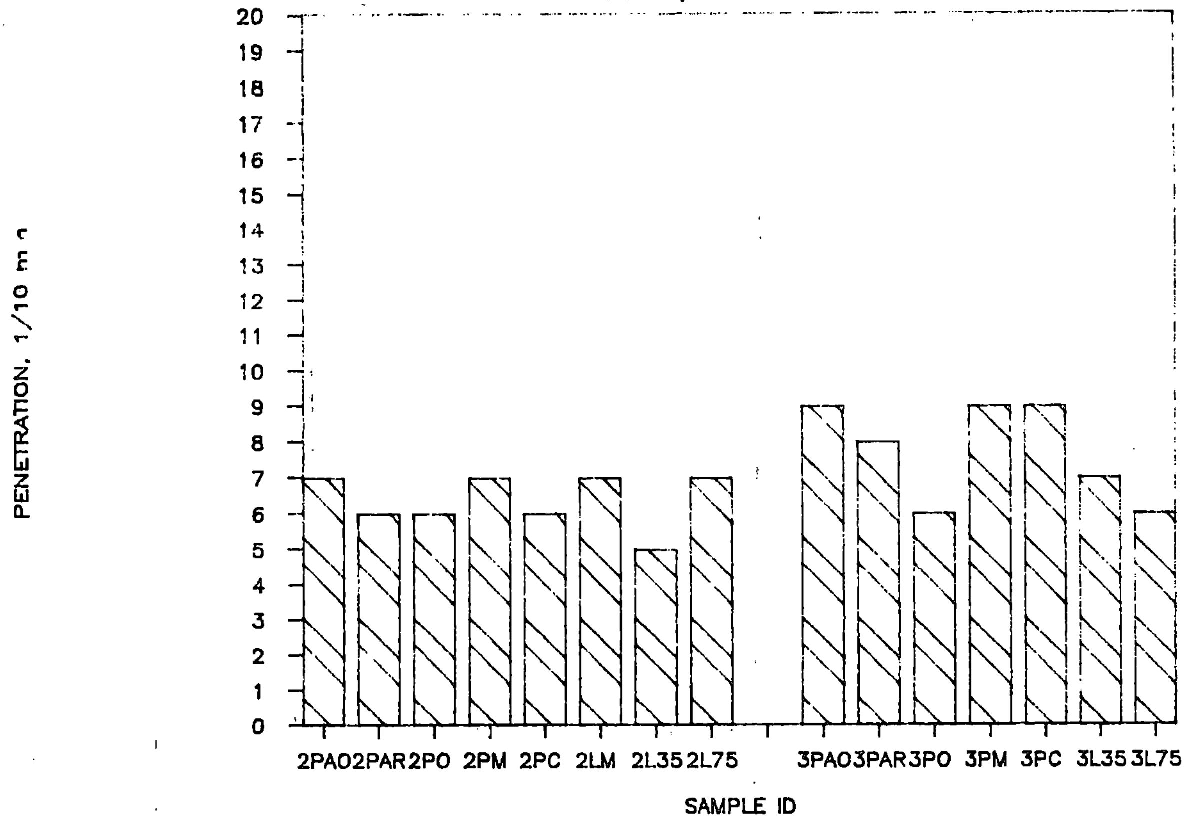
Physical Properties of AC-20 Asphalts.


PENETRATION AT 4 C
AC-20, PROJECT 2 & 3
PENETRATION, 1/10 mm
70
60
50
40
30
20
10
0
2PAO 2PAR 2PO 2PM 2PC 2LM 2L35 2L75 3PAO 3PAR 3PO 3PM 3PC 3L35 3L75
SAMPLE ID


PENETRATION AT 4 C
AC-20, PROJECT 10 & 12
PENETRATION, 1/10 mm
70
60
50
40
30
20
10
0
10PAO 10PAR 10PO 10L35 10L75 12PAO 12PAR 12PO 12L35 12L50 12L75
SAMPLE ID

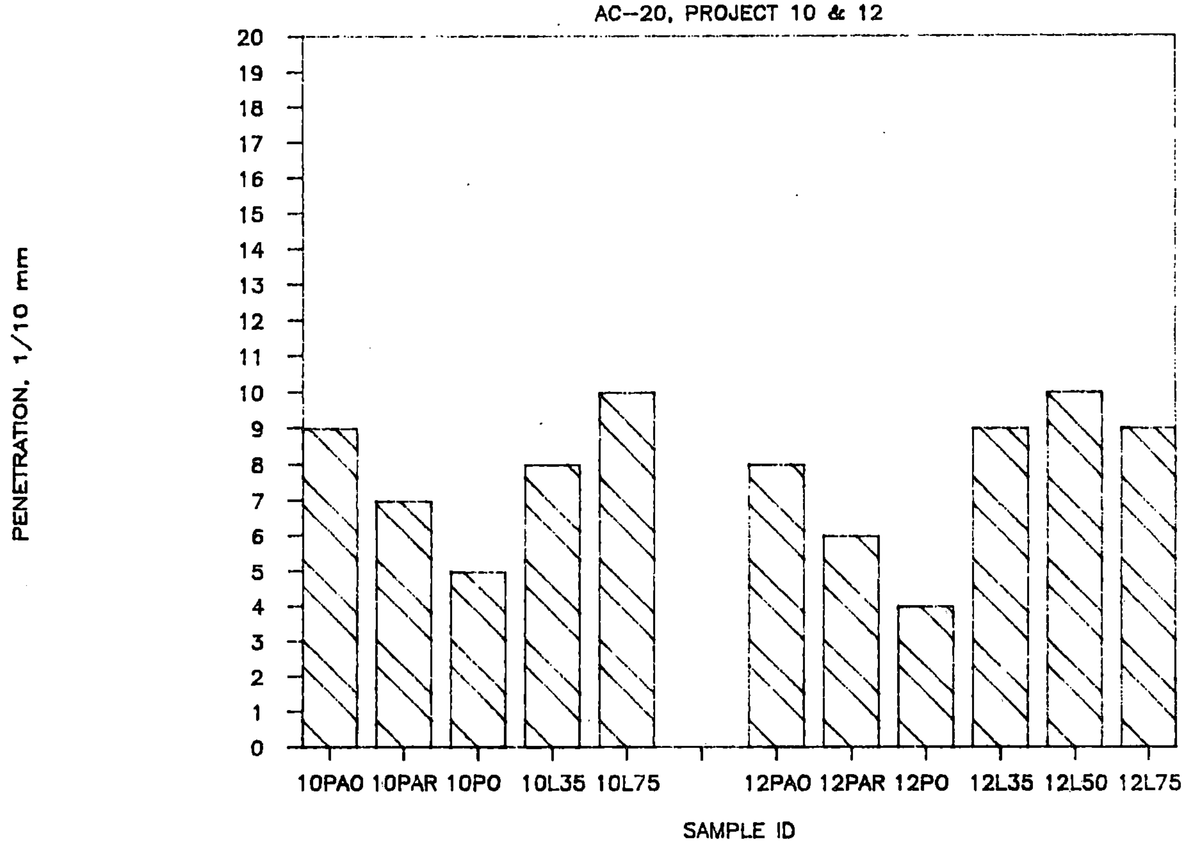
PENETRATION AT 5 C

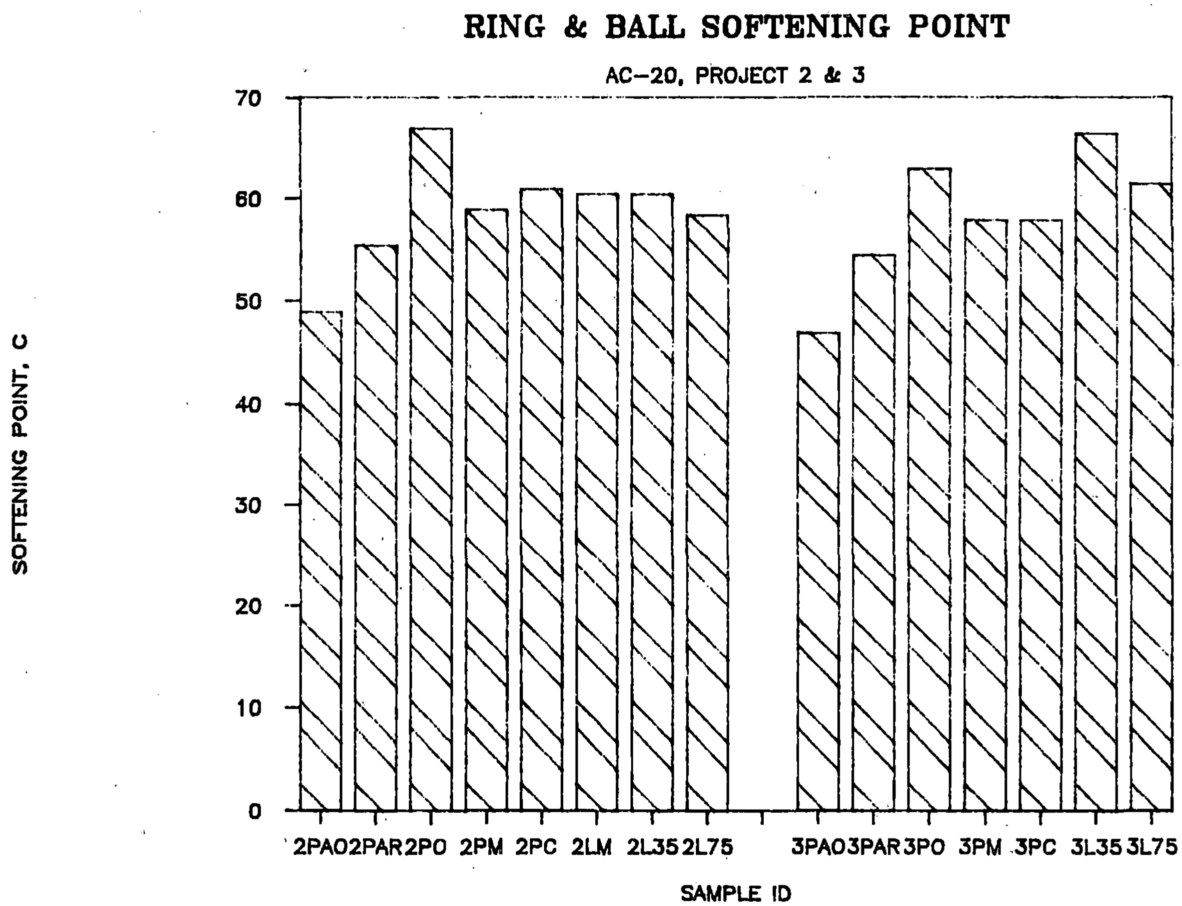
AC-20, PROJECT 2 & 3

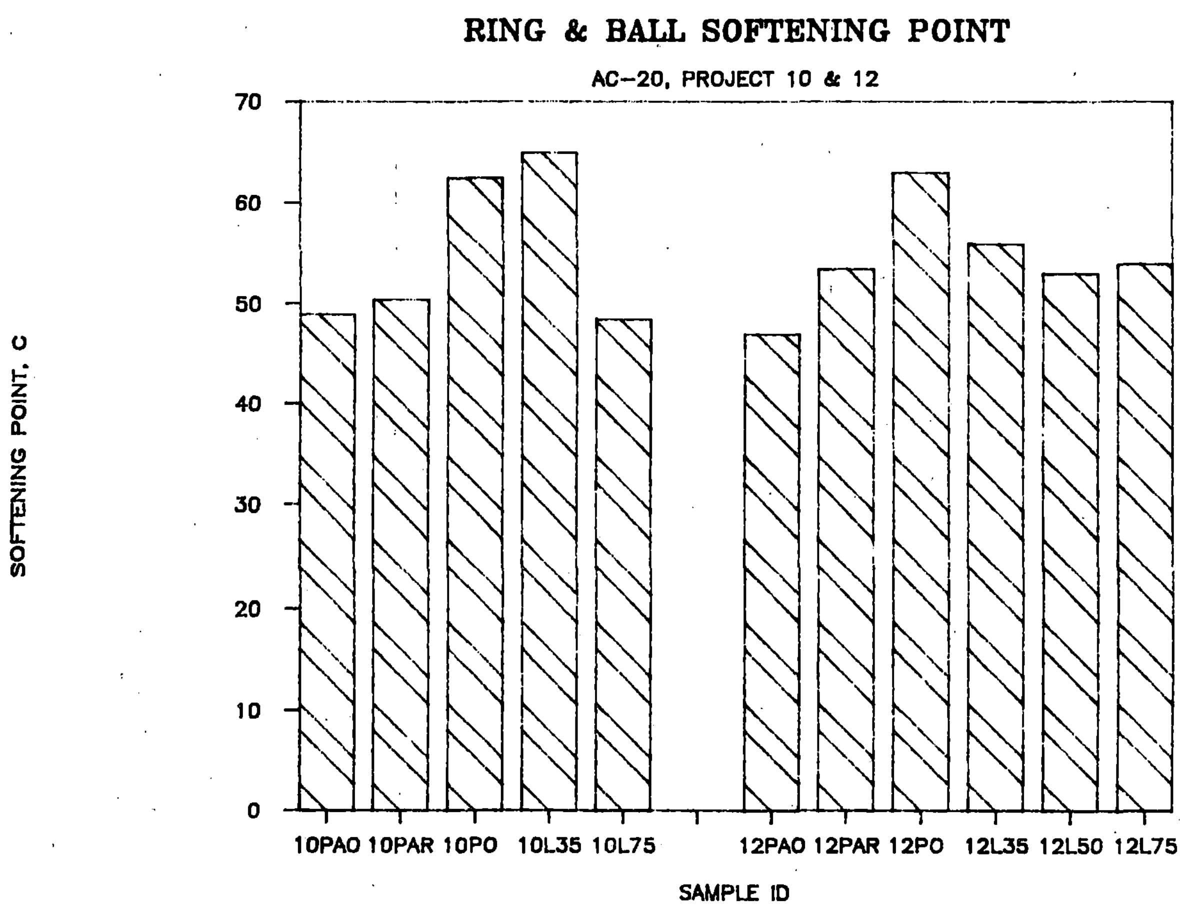


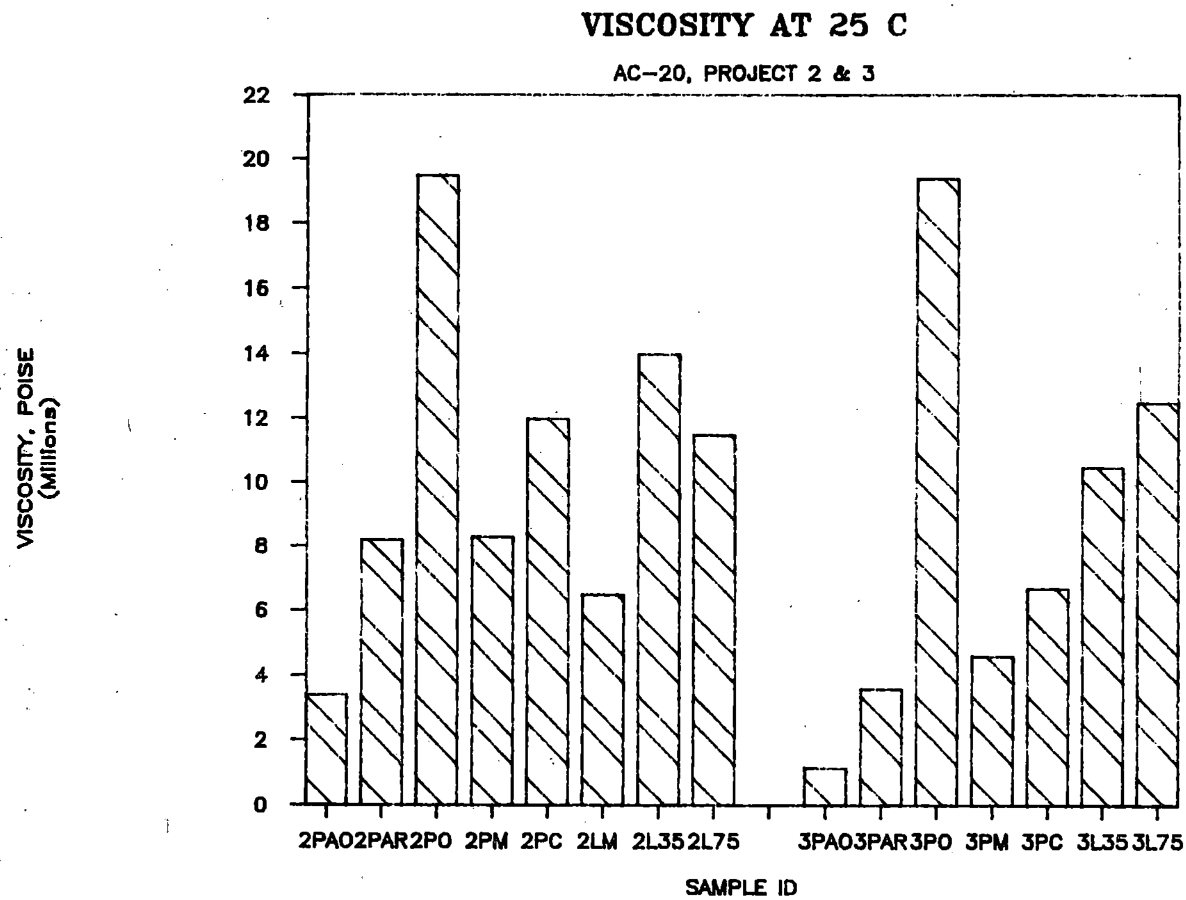
PENETRATION AT 5 C

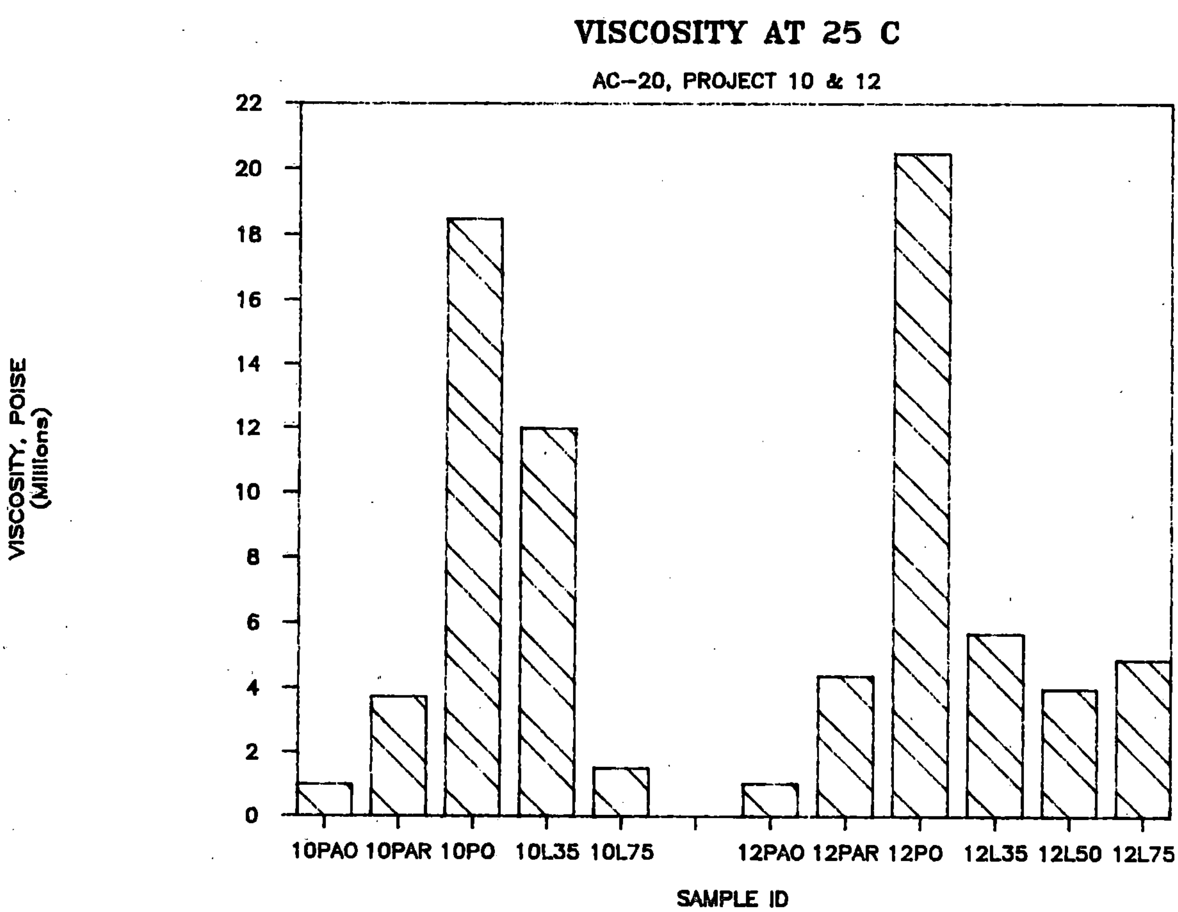
AC-20, PROJECT 10 & 12




RING & BALL SOFTENING POINT
AC-20, PROJECT 2 & 3
SOFTENING POINT, C
70
60
50
40
30
20
10
0
2PAO
2PAR
2PO
2PM
2PC
2LM
2L35
2L75
3PAO
3PAR
3PO
3PM
3PC
3L35
3L75
SAMPLE ID


RING & BALL SOFTENING POINT
AC-20, PROJECT 10 & 12
SOFTENING POINT, C
70
60
50
40
30
20
10
0
10PAO
10PAR
10PO
10L35
10L75
12PAO
12PAR
12PO
12L35
12L50
12L75
SAMPLE ID


VISCOSITY AT 25 C
AC-20, PROJECT 2 & 3
VISCOSITY, POISE
(Millions)
22
20
18
16
14
12
10
8
6
4
2
0
2PAO
2PAR
2PO
2PM
2PC
2LM
2L35
2L75
3PAO
3PAR
3PO
3PM
3PC
3L35
3L75
SAMPLE ID


VISCOSITY AT 25 C
AC-20, PROJECT 10 & 12
VISCOSITY, POISE
(Millions)
22
20
18
16
14
12
10
8
6
4
2
0
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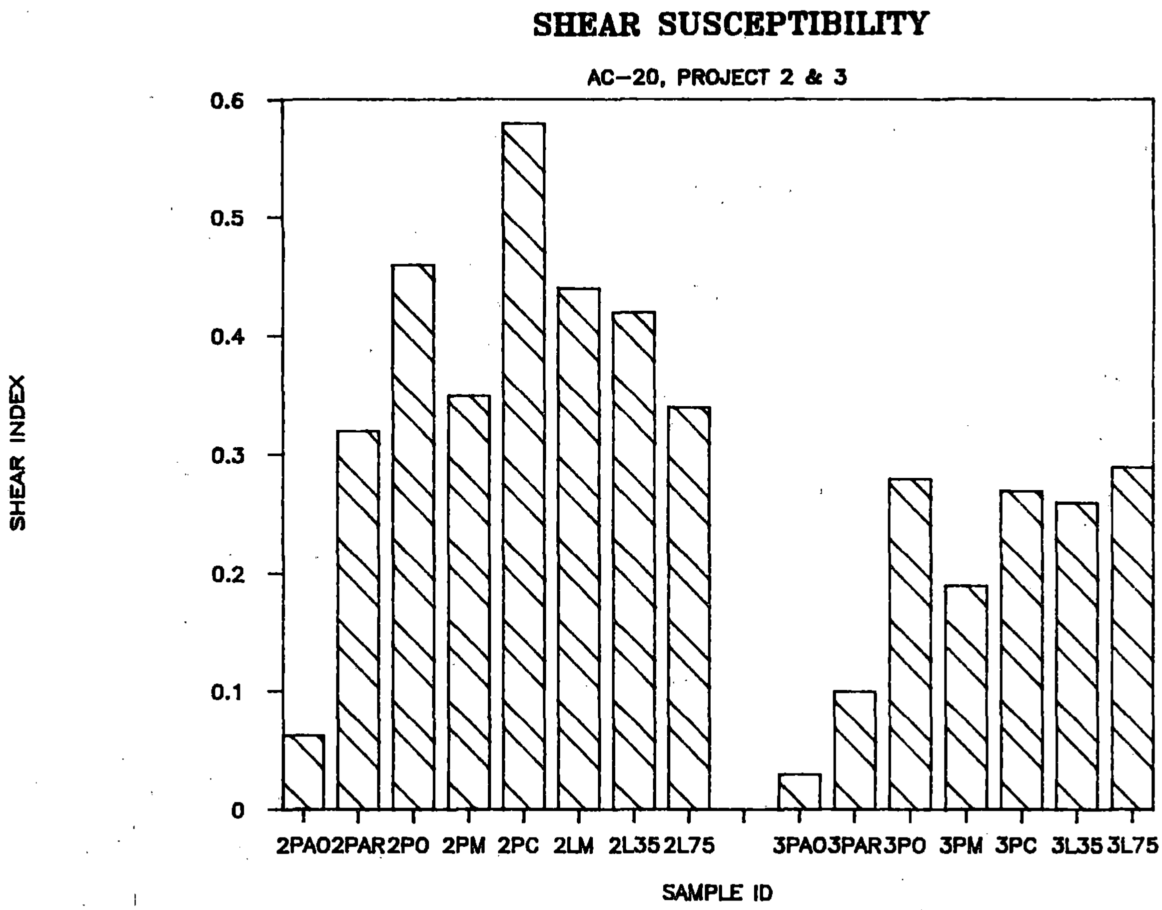
10PAR
10PO
10L35
10L75
12PAO
12PAR
12PO
12L35
12L50
12L75
SAMPLE ID


SHEAR SUSCEPTIBILITY
AC-20, PROJECT 2 & 3
SHEAR INDEX
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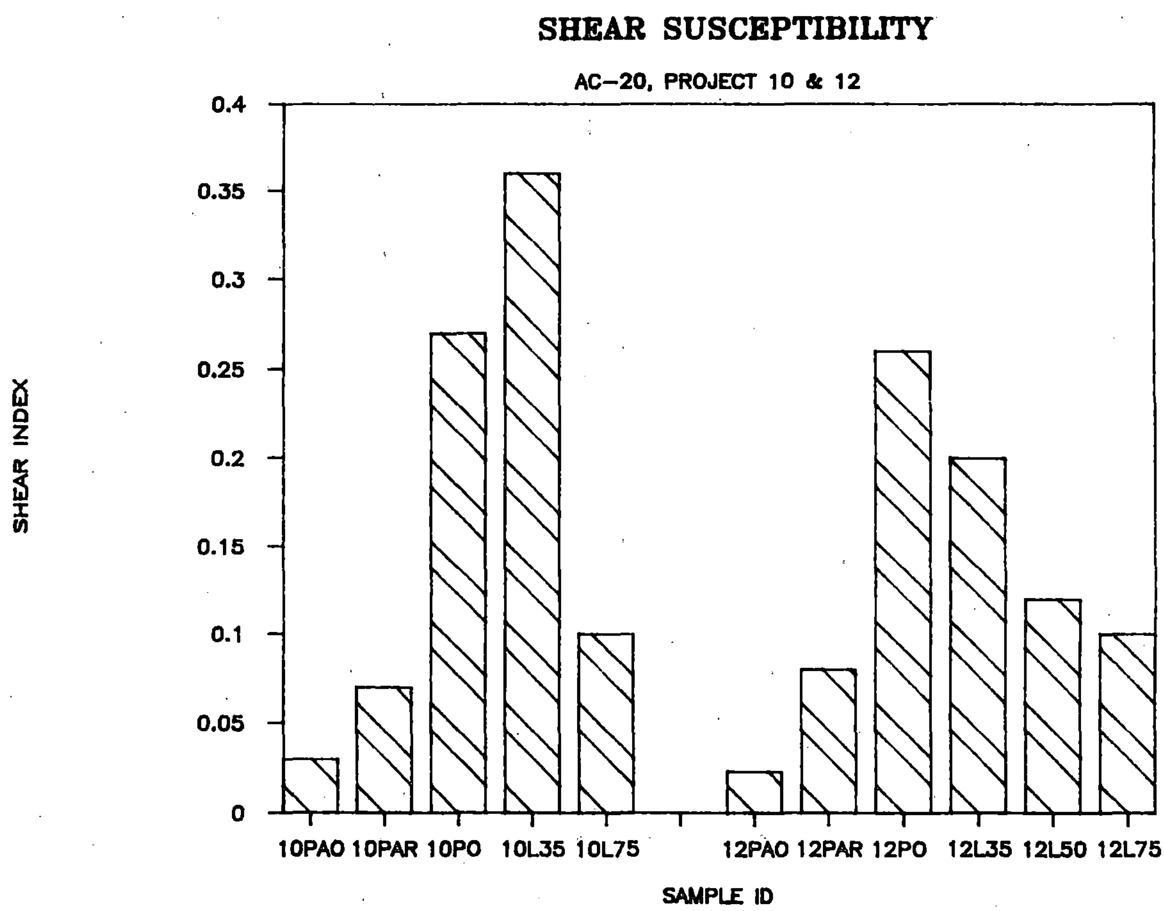
0.5
0.4
0.3
0.2
0.1
0
2PAO 2PAR 2PO 2PM 2PC 2LM 2L35 2L75 3PAO 3PAR 3PO 3PM 3PC 3L35 3L75
SAMPLE ID


SHEAR SUSCEPTIBILITY
AC-20, PROJECT 10 & 12
SHEAR INDEX
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0.3
0.25
0.2
0.15
0.1
0.05
0
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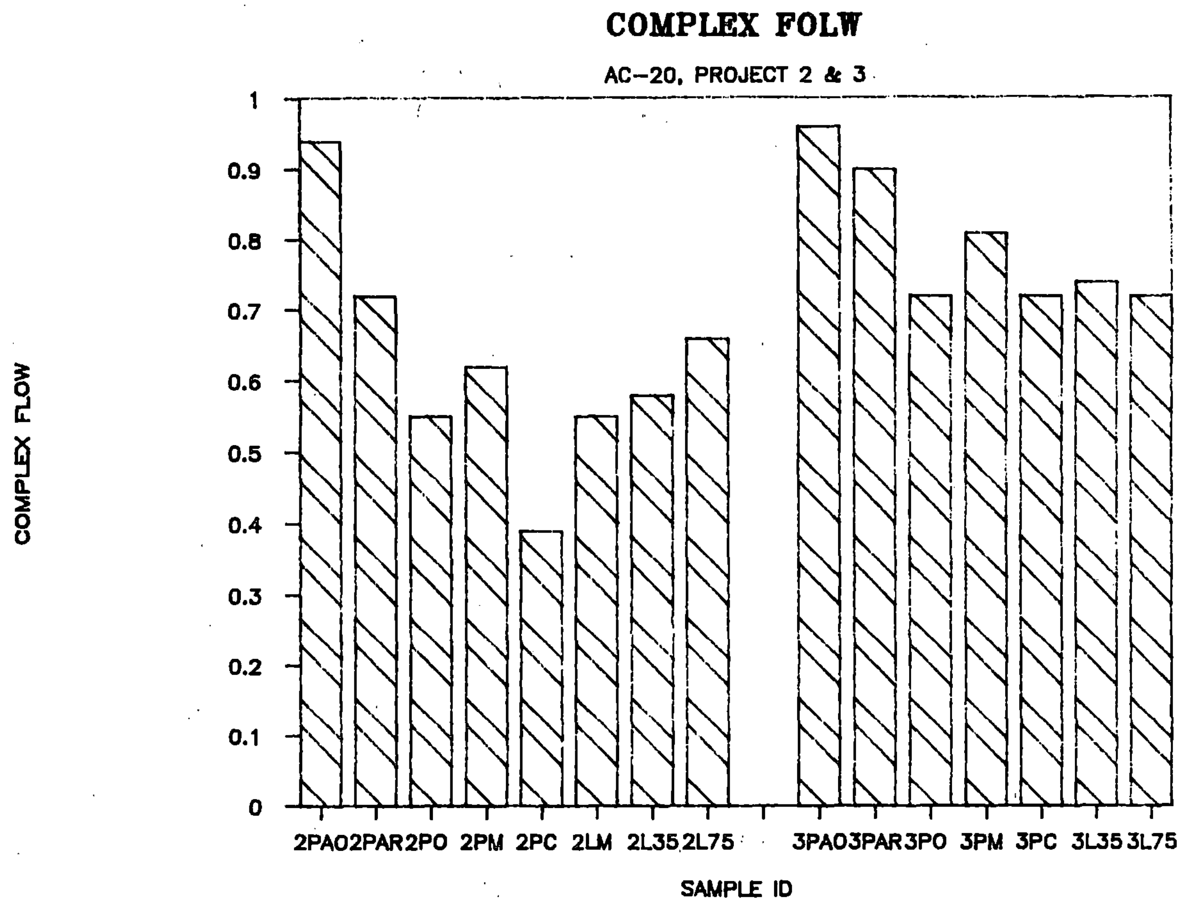
SAMPLE ID


COMPLEX FOLW
AC-20, PROJECT 2 & 3
COMPLEX FLOW
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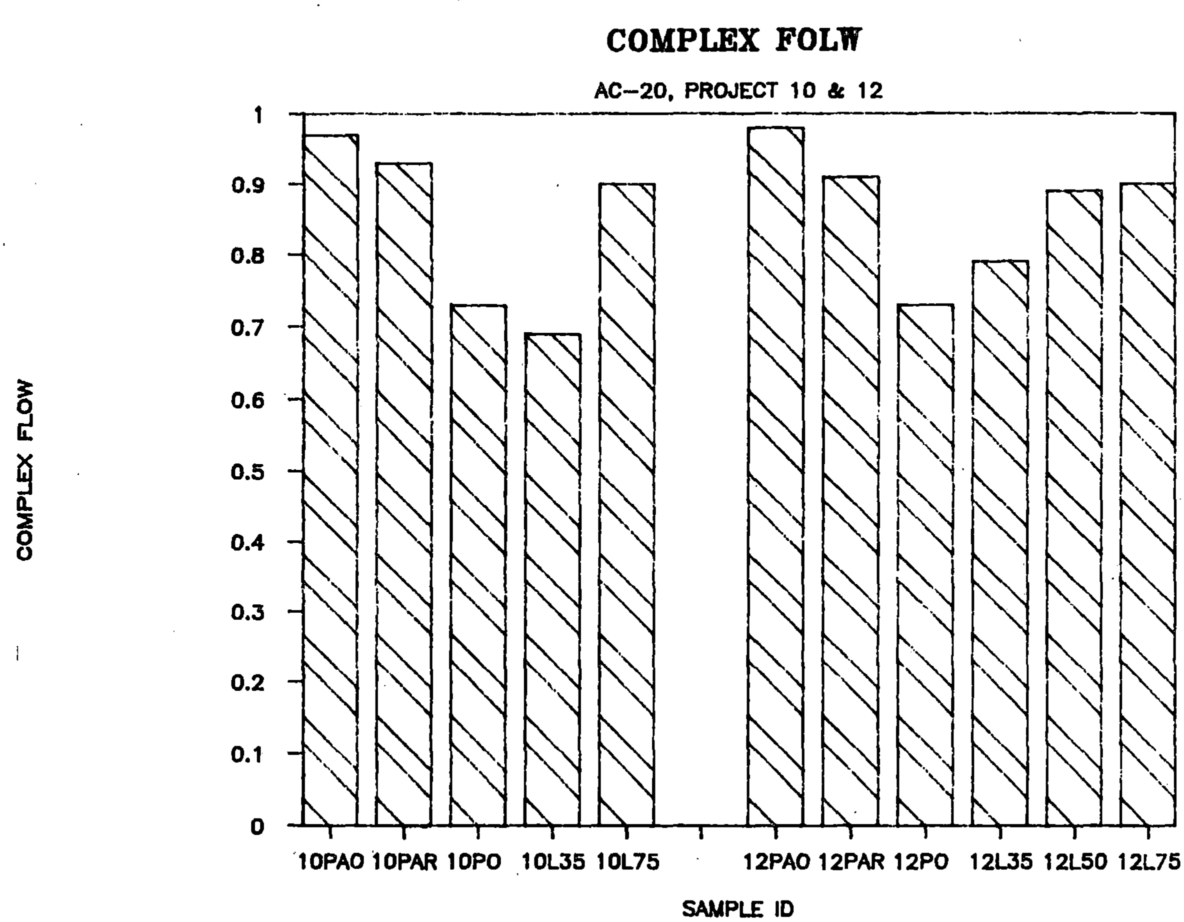
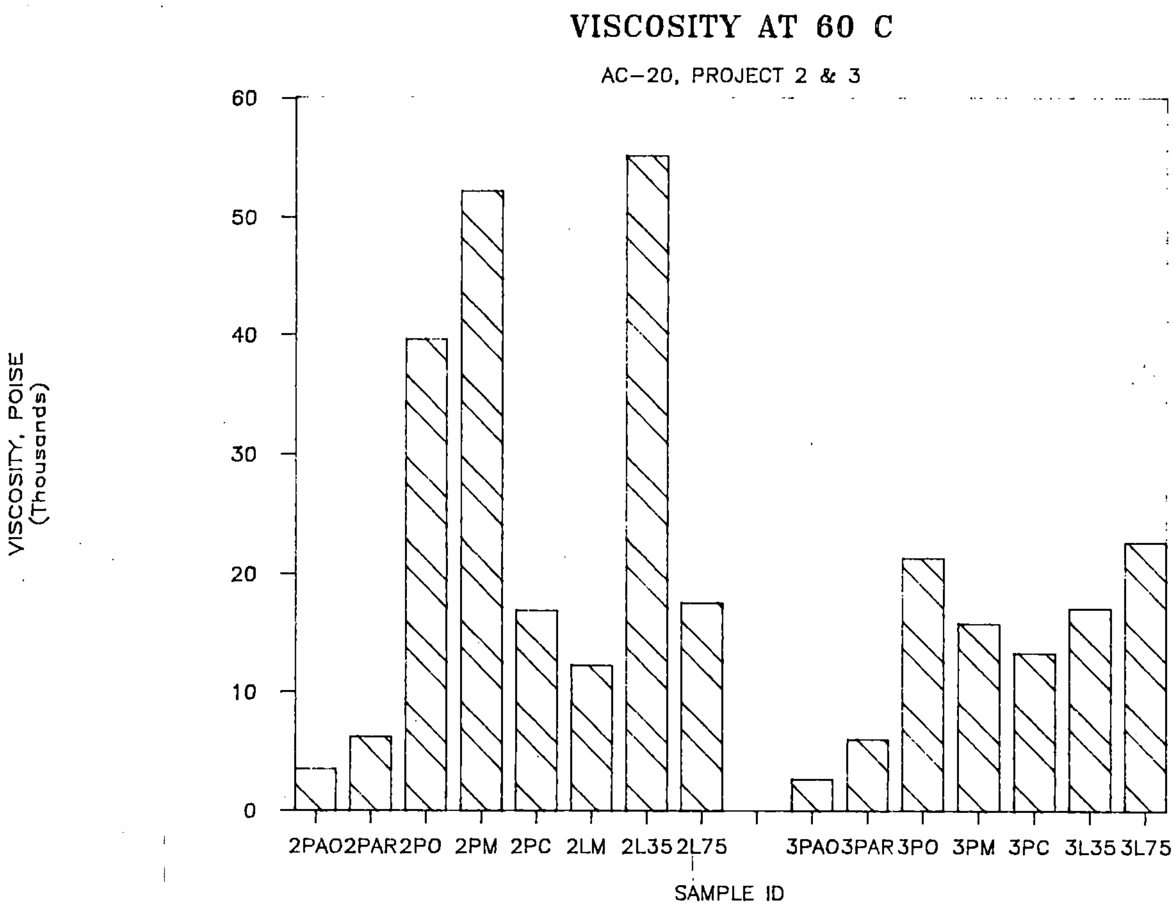
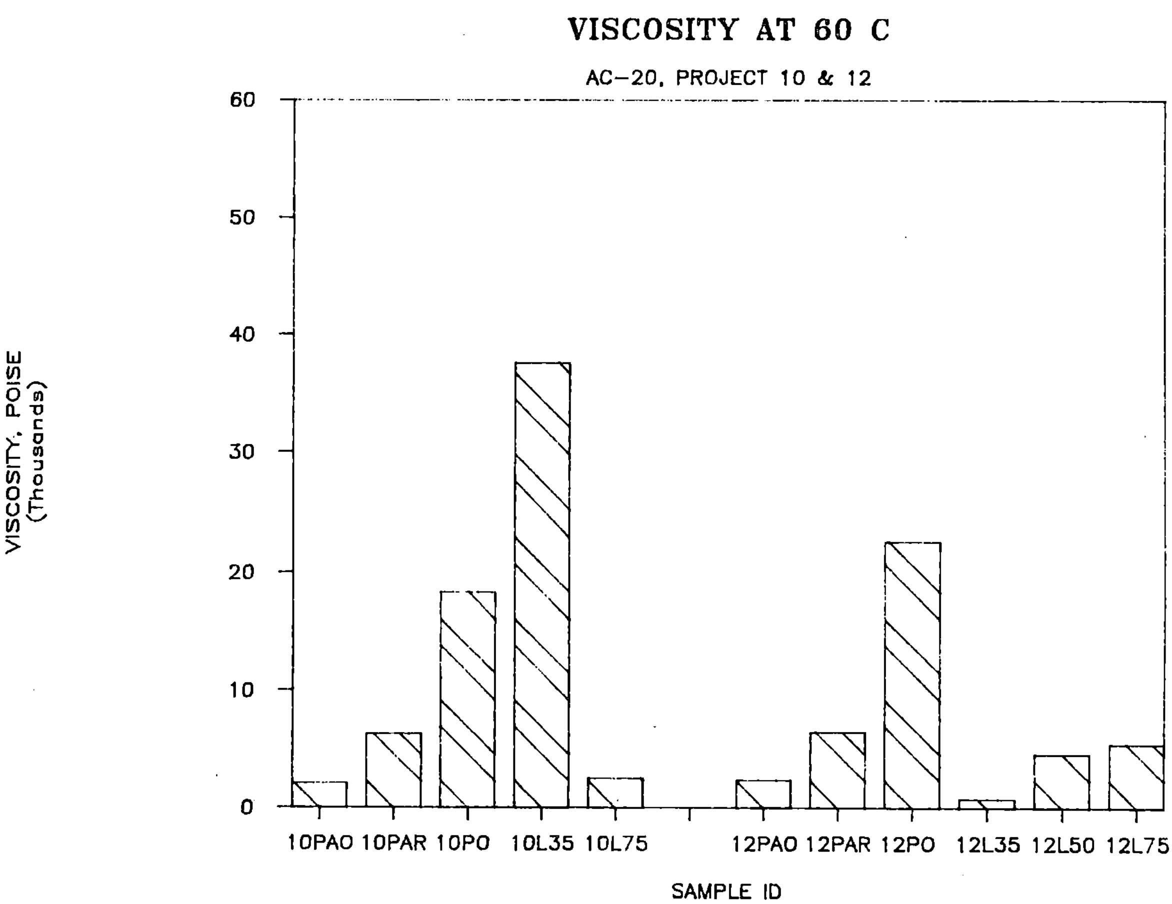
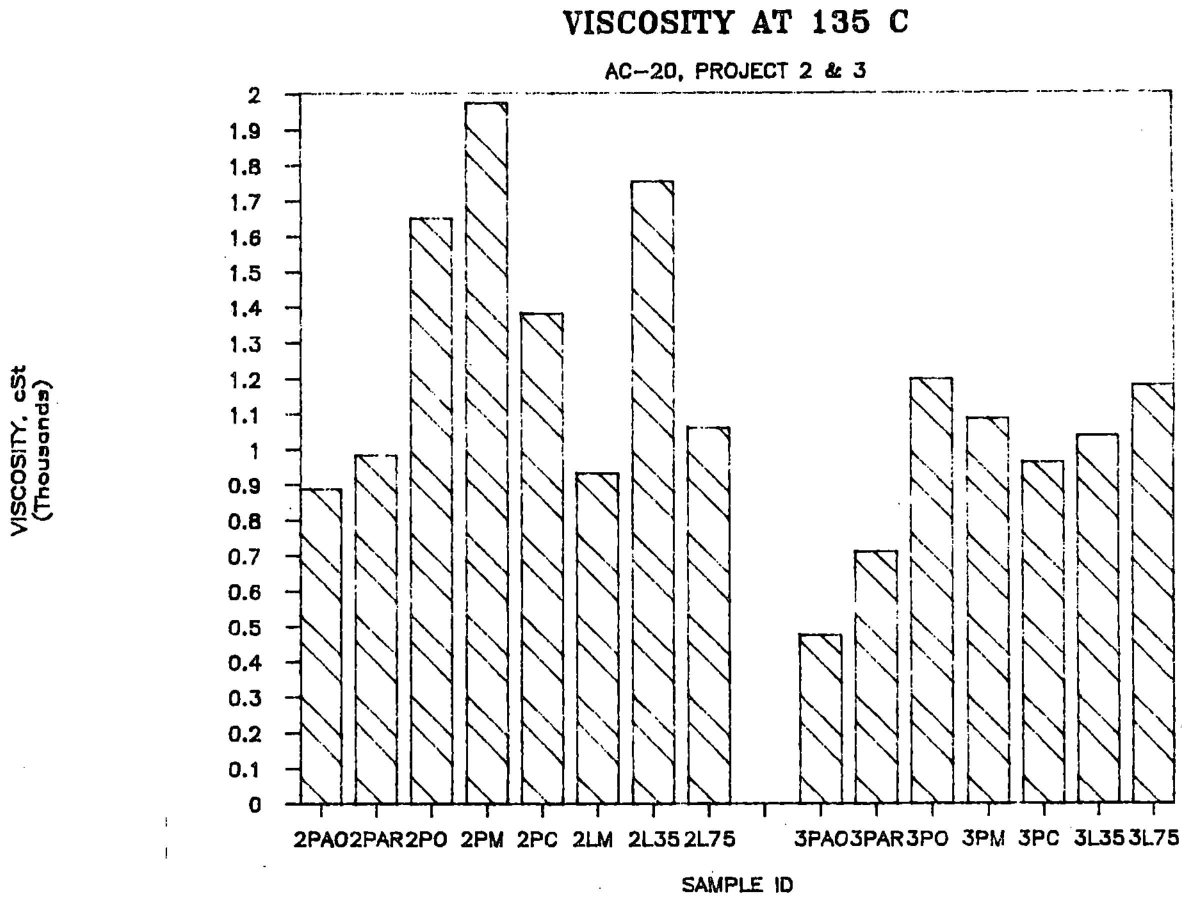
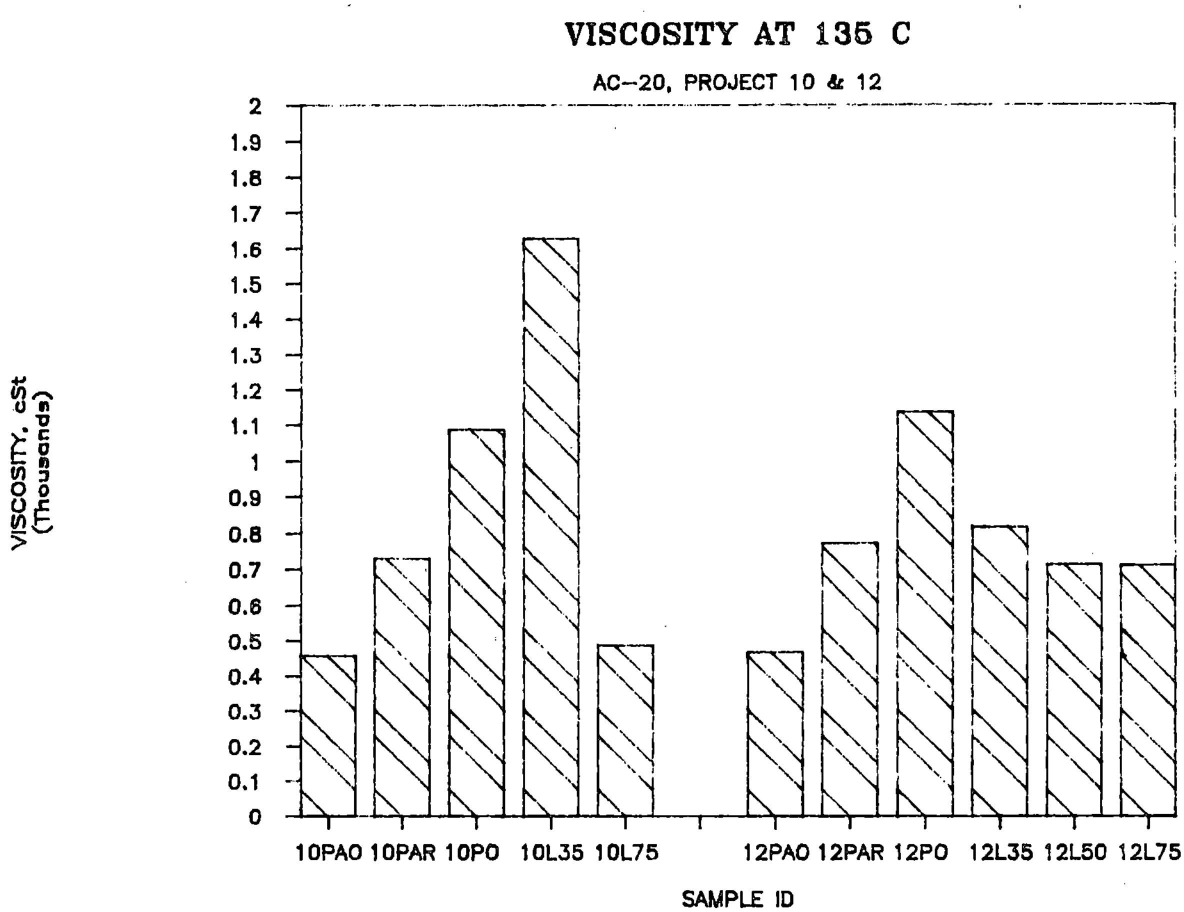
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2PAO
2PAR
2PO
2PM
2PC
2LM
2L35
2L75
3PAO
3PAR
3PO
3PM
3PC
3L35
3L75
SAMPLE ID

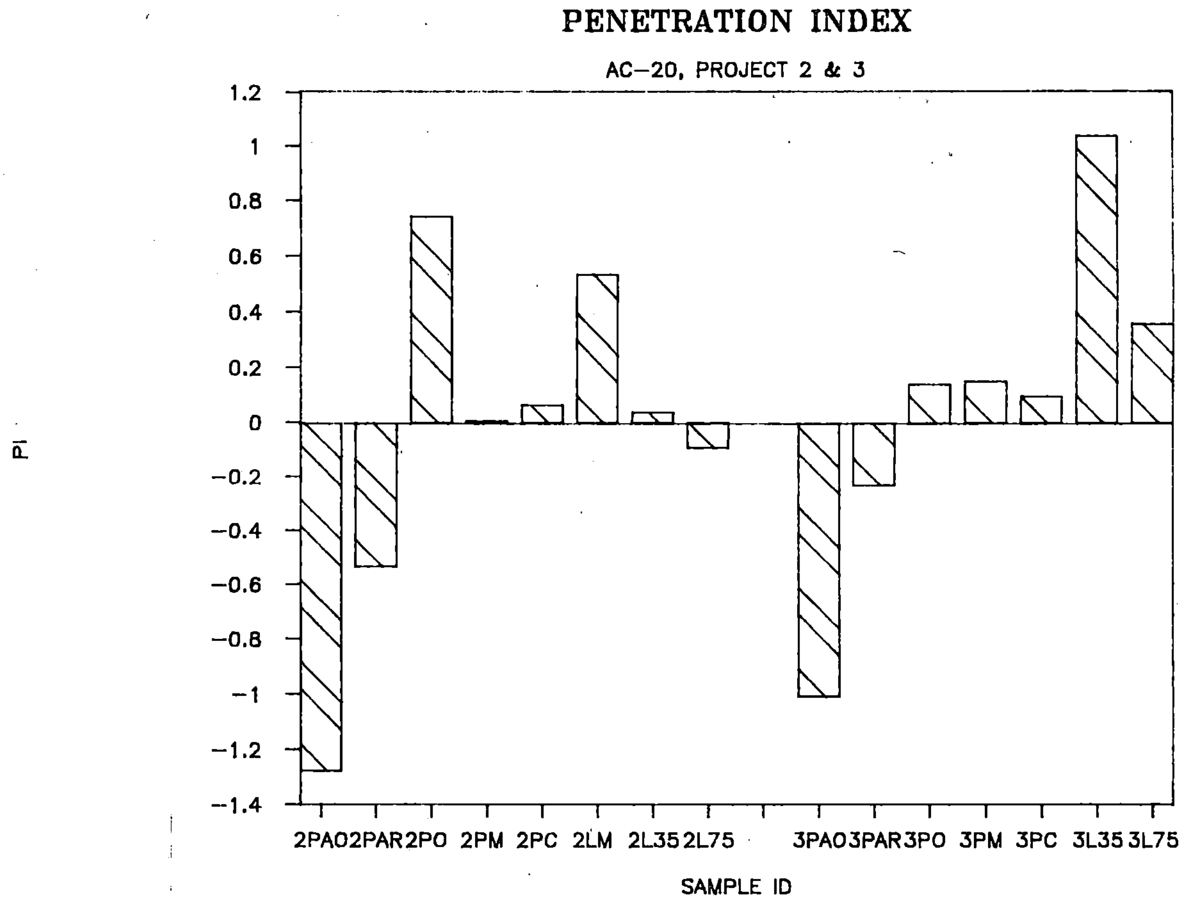

COMPLEX FOLW
AC-20, PROJECT 10 & 12
COMPLEX FLOW
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10PAO
10PAR
10PO
10L35
10L75
12PAO
12PAR
12PO
12L35
12L50
12L75
SAMPLE ID

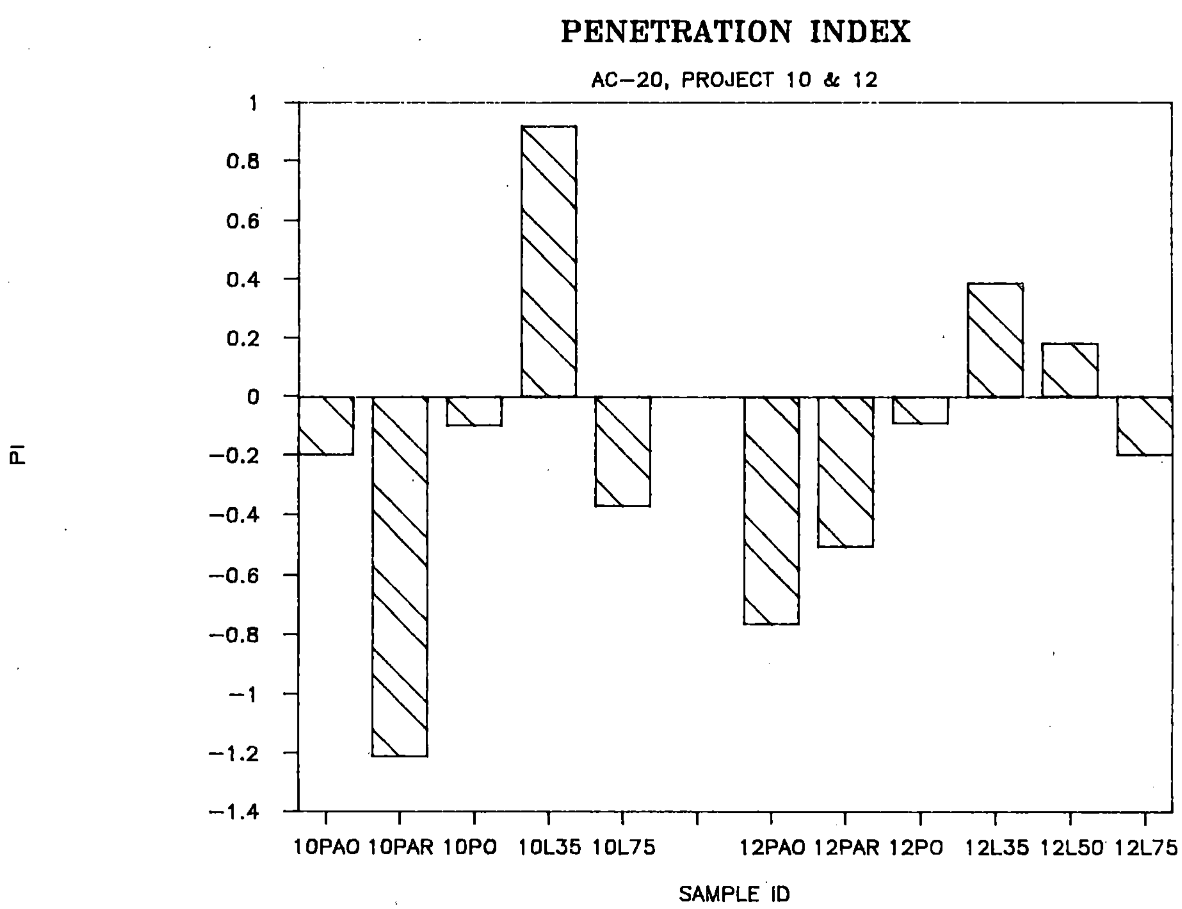

VISCOSITY AT 60 C
AC-20, PROJECT 2 & 3
VISCOSITY, POISE
(Thousands)
0
10
20
30
40
50
60
2PAO
2PAR
2PO
2PM
2PC
2LM
2L35
2L75
3PAO
3PAR
3PO
3PM
3PC
3L35
3L75
SAMPLE ID

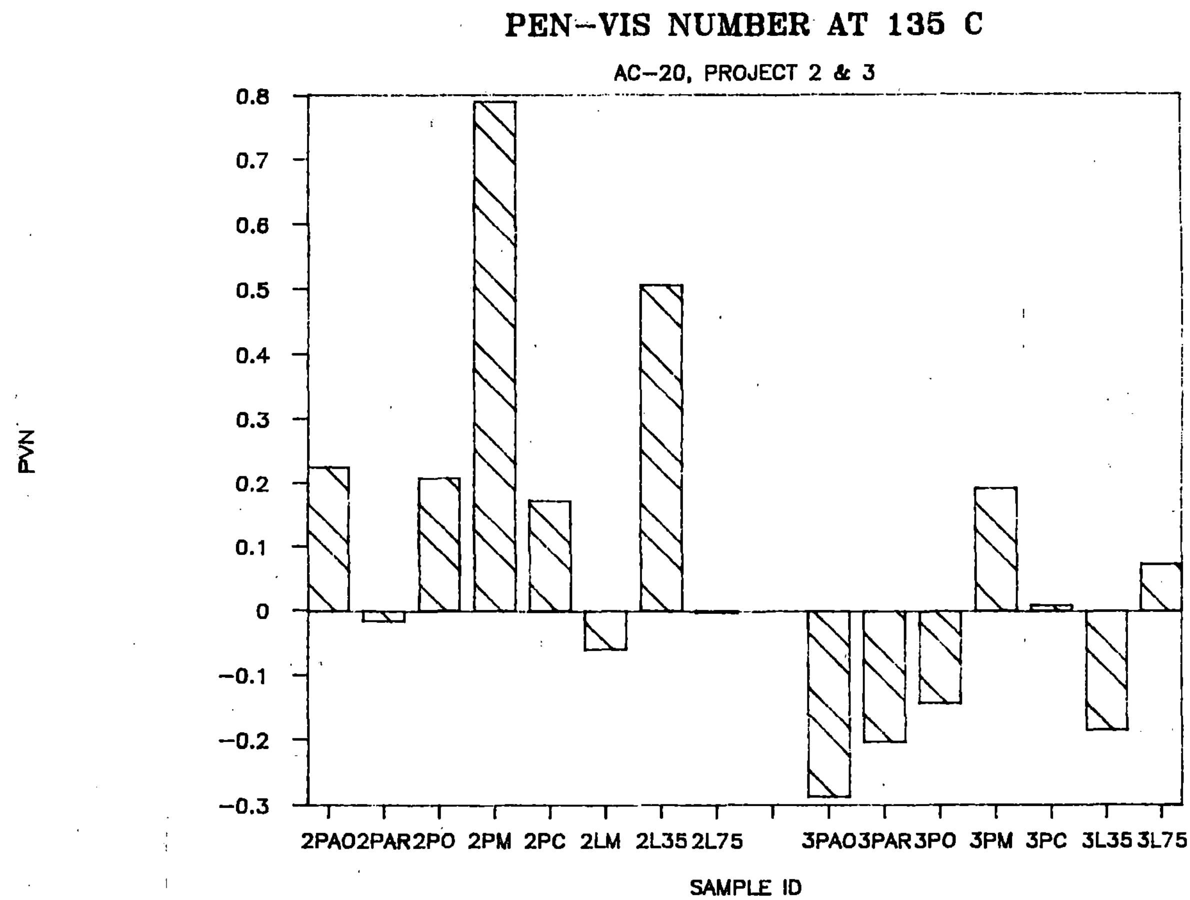

VISCOSITY AT 60 C
AC-20, PROJECT 10 & 12
VISCOSITY, POISE
(Thousands)
0
10
20
30
40
50
60
10PAO
10PAR
10PO
10L35
10L75
12PAO
12PAR
12PO
12L35
12L50
12L75
SAMPLE ID

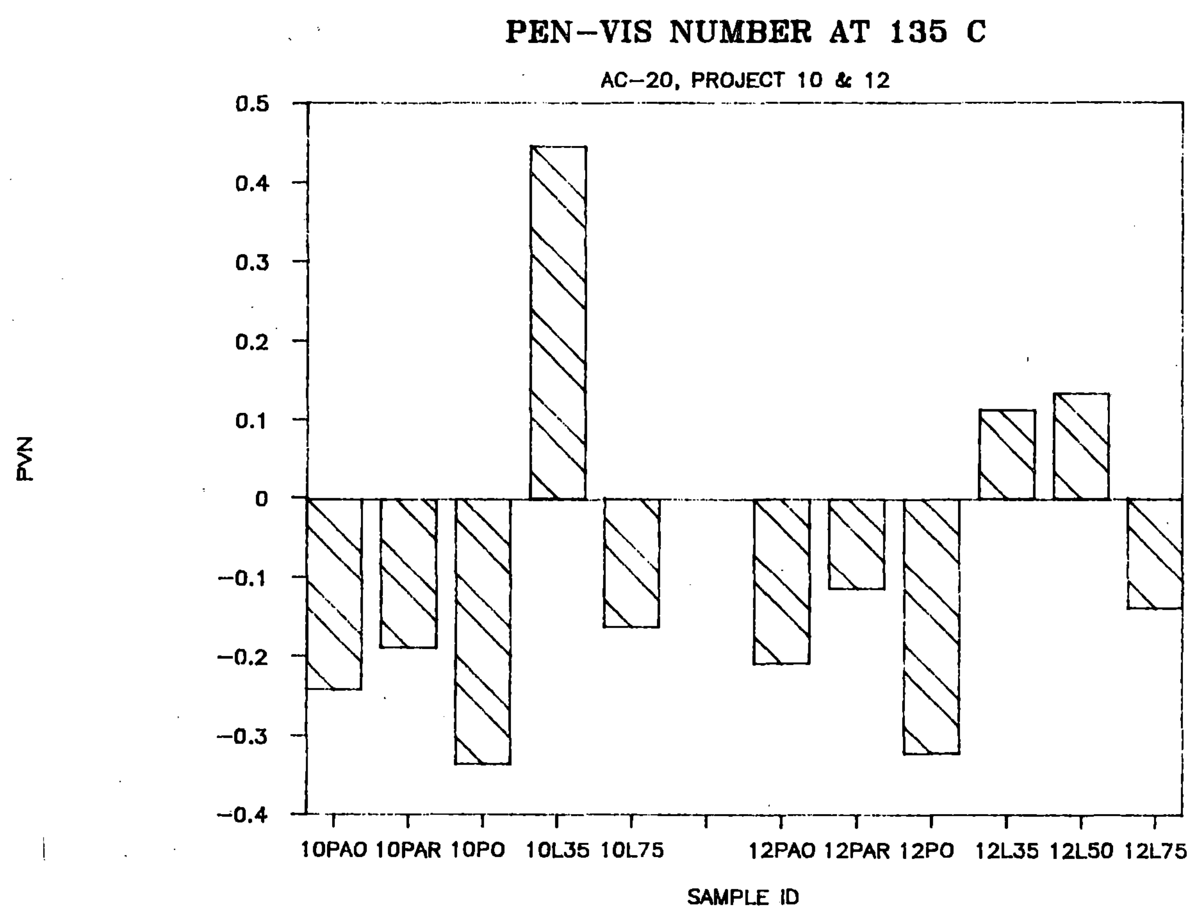

VISCOSITY AT 135 C
AC-20, PROJECT 2 & 3
VISCOSITY, cSt
(Thousands)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2PAO 2PAR 2PO 2PM 2PC 2LM 2L35 2L75 3PAO 3PAR 3PO 3PM 3PC 3L35 3L75
SAMPLE ID

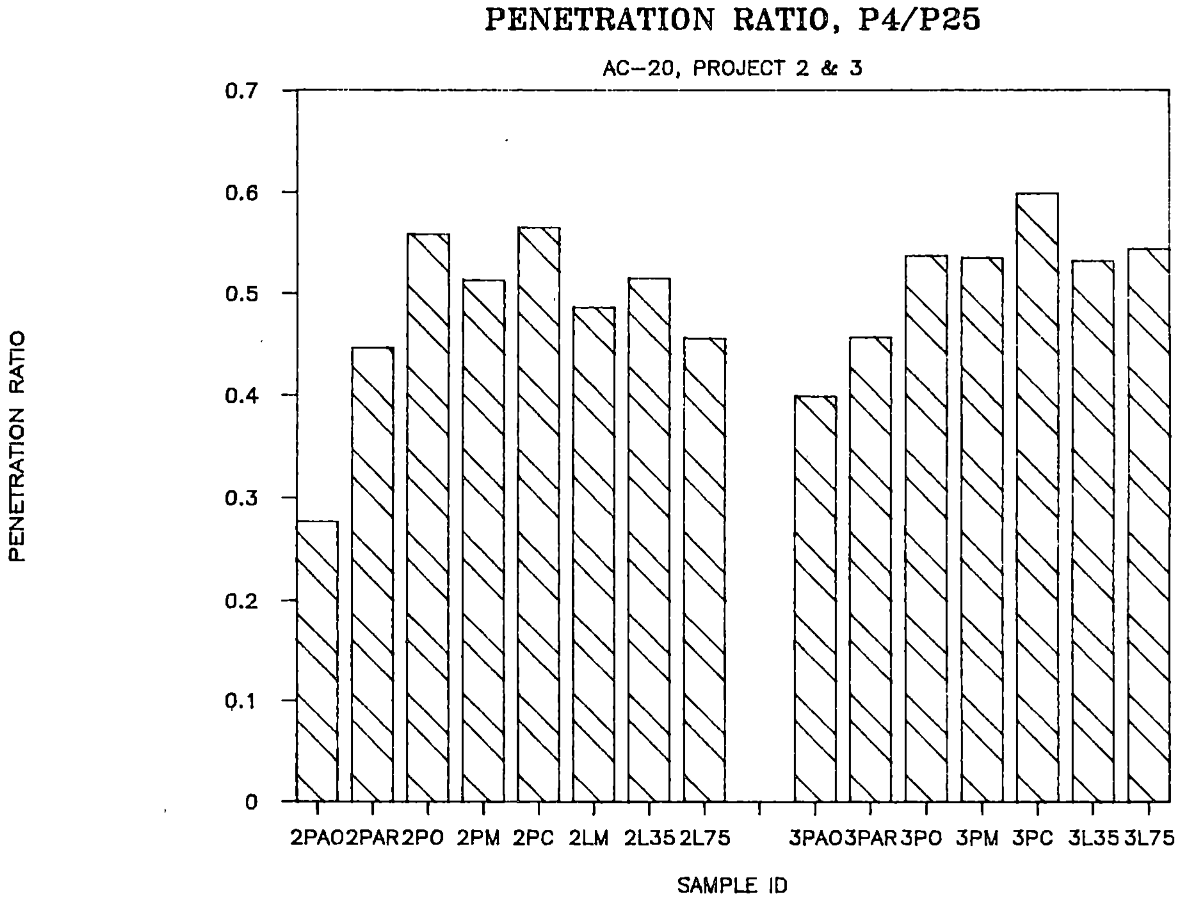

VISCOSITY AT 135 C
AC-20, PROJECT 10 & 12
VISCOSITY, cSt
(Thousands)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10PAO 10PAR 10PO 10L35 10L75 12PAO 12PAR 12PO 12L35 12L50 12L75
SAMPLE ID

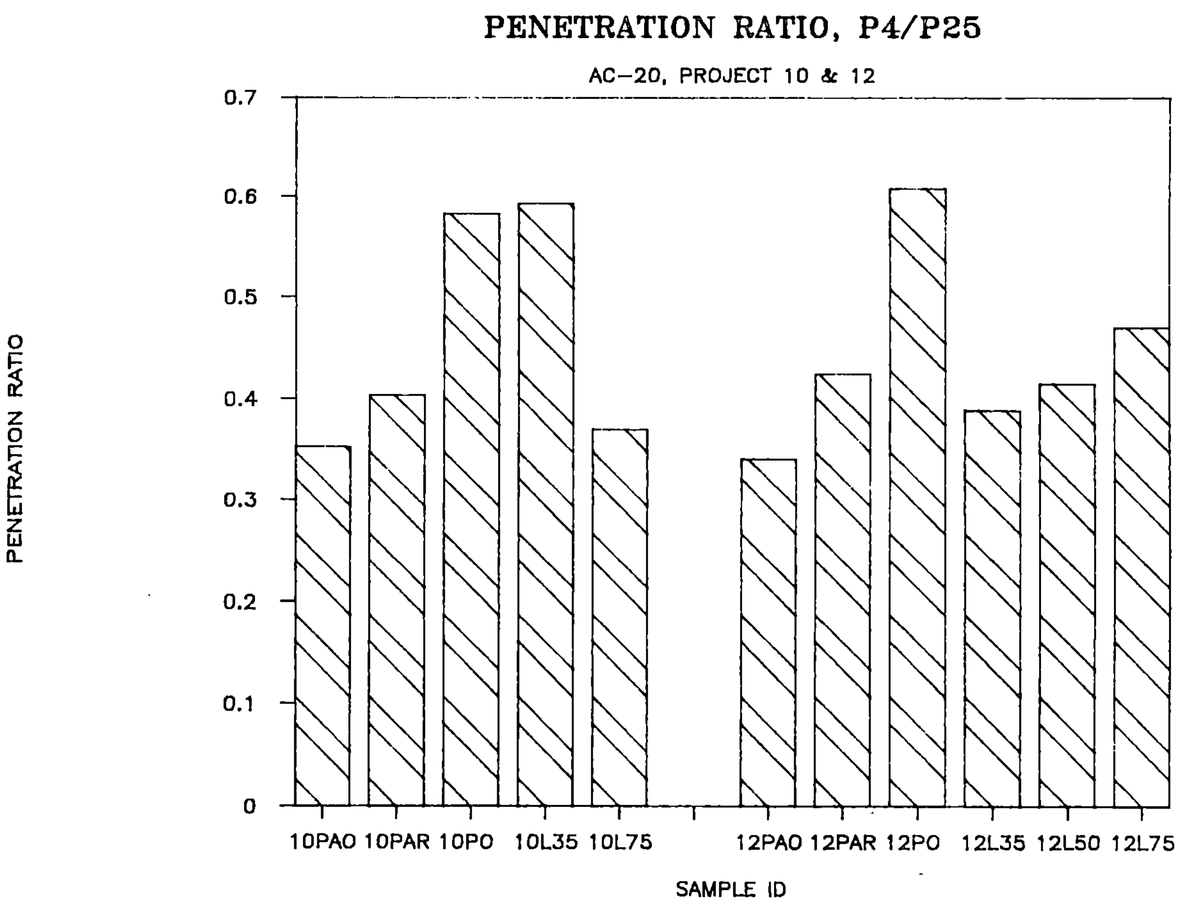

PENETRATION INDEX
AC-20, PROJECT 2 & 3
PI
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
2PAO 2PAR 2PO 2PM 2PC 2LM 2L35 2L75 3PAO 3PAR 3PO 3PM 3PC 3L35 3L75
SAMPLE ID

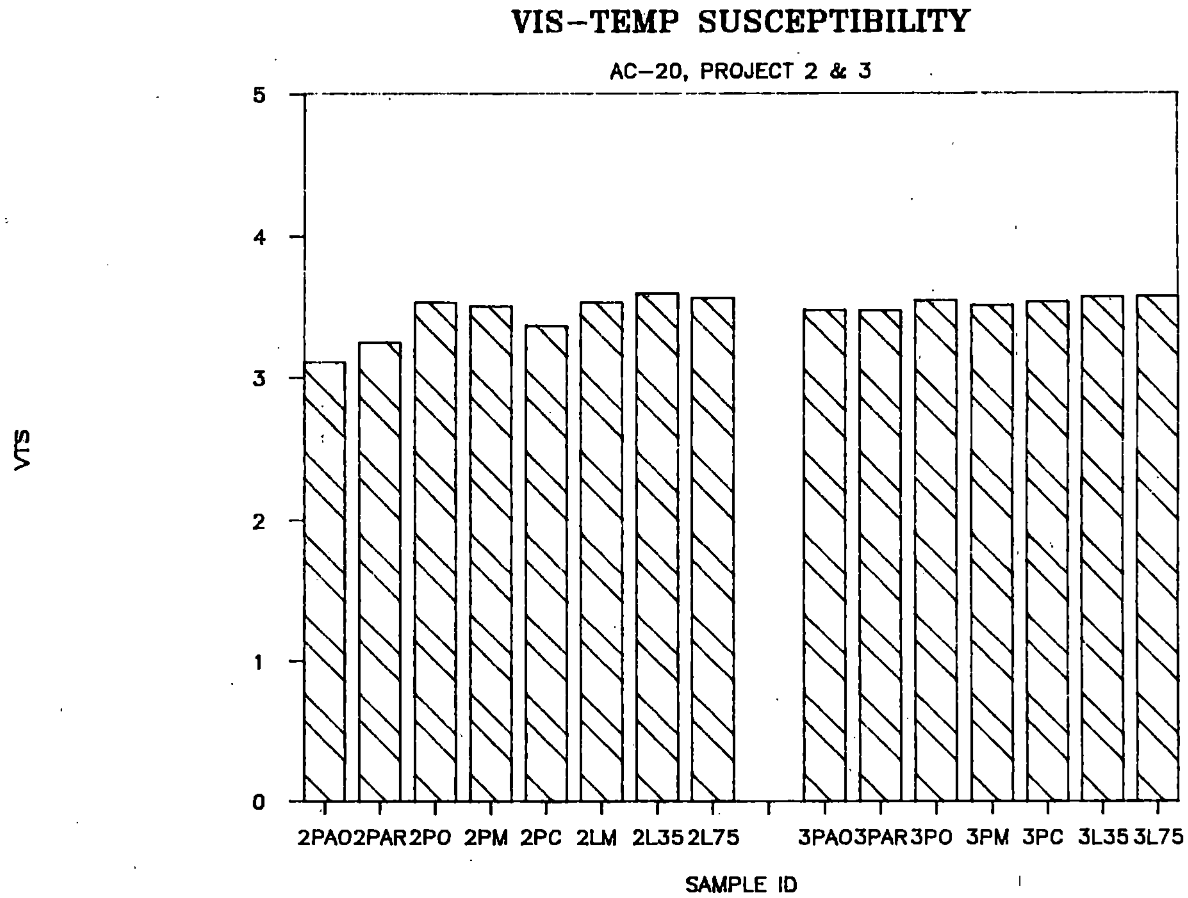

PENETRATION INDEX
AC-20, PROJECT 10 & 12
PI
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
10PAO 10PAR 10PO 10L35 10L75 12PAO 12PAR 12PO 12L35 12L50 12L75
SAMPLE ID

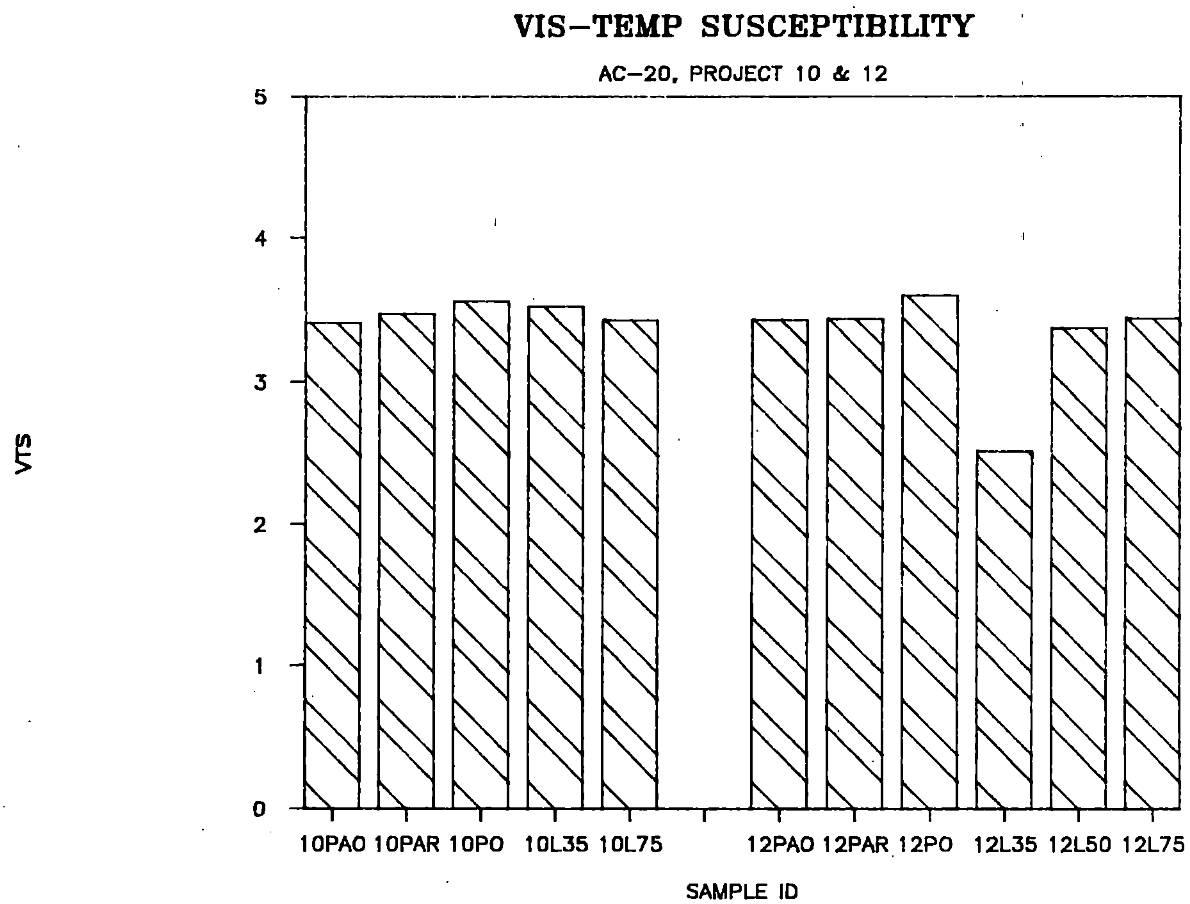

PEN-VIS NUMBER AT 135 C
AC-20, PROJECT 2 & 3
PVN
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
2PAO 2PAR 2PO 2PM 2PC 2LM 2L35 2L75 3PAO 3PAR 3PO 3PM 3PC 3L35 3L75
SAMPLE ID

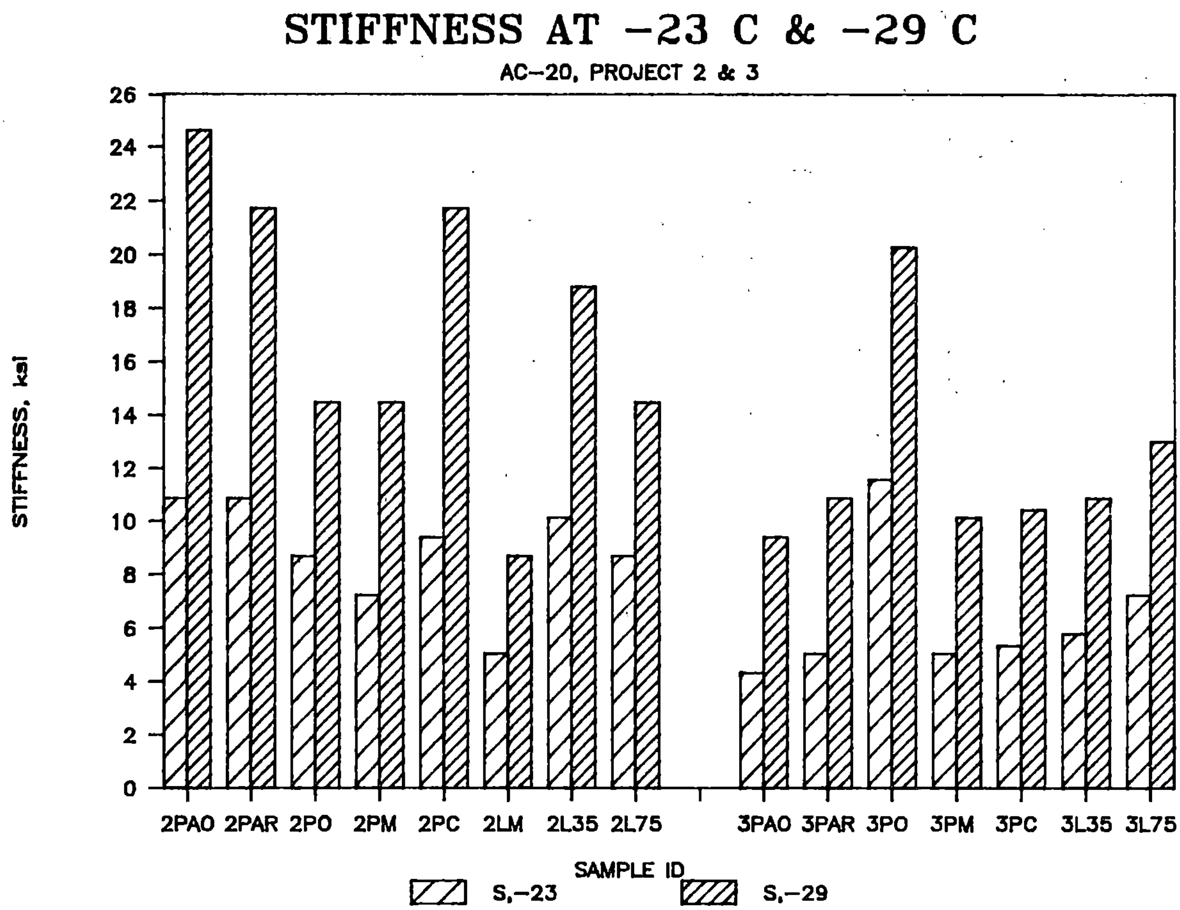

PEN-VIS NUMBER AT 135 C
AC-20, PROJECT 10 & 12
PVN
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
10PAO 10PAR 10PO 10L35 10L75 12PAO 12PAR 12PO 12L35 12L50 12L75
SAMPLE ID

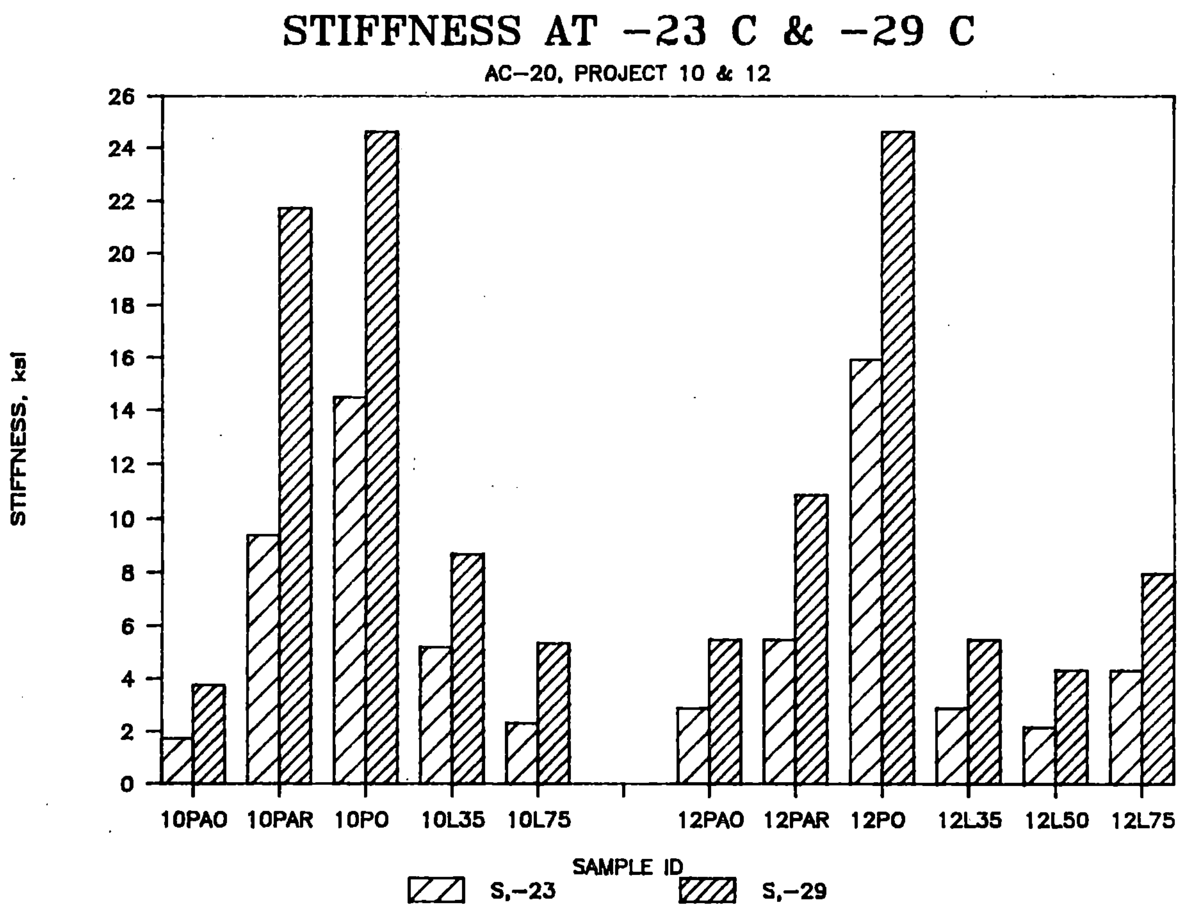

PENETRATION RATIO, P4/P25
AC-20, PROJECT 2 & 3
PENETRATION RATIO
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2PAO 2PAR 2PO 2PM 2PC 2LM 2L35 2L75
3PAO 3PAR 3PO 3PM 3PC 3L35 3L75
SAMPLE ID

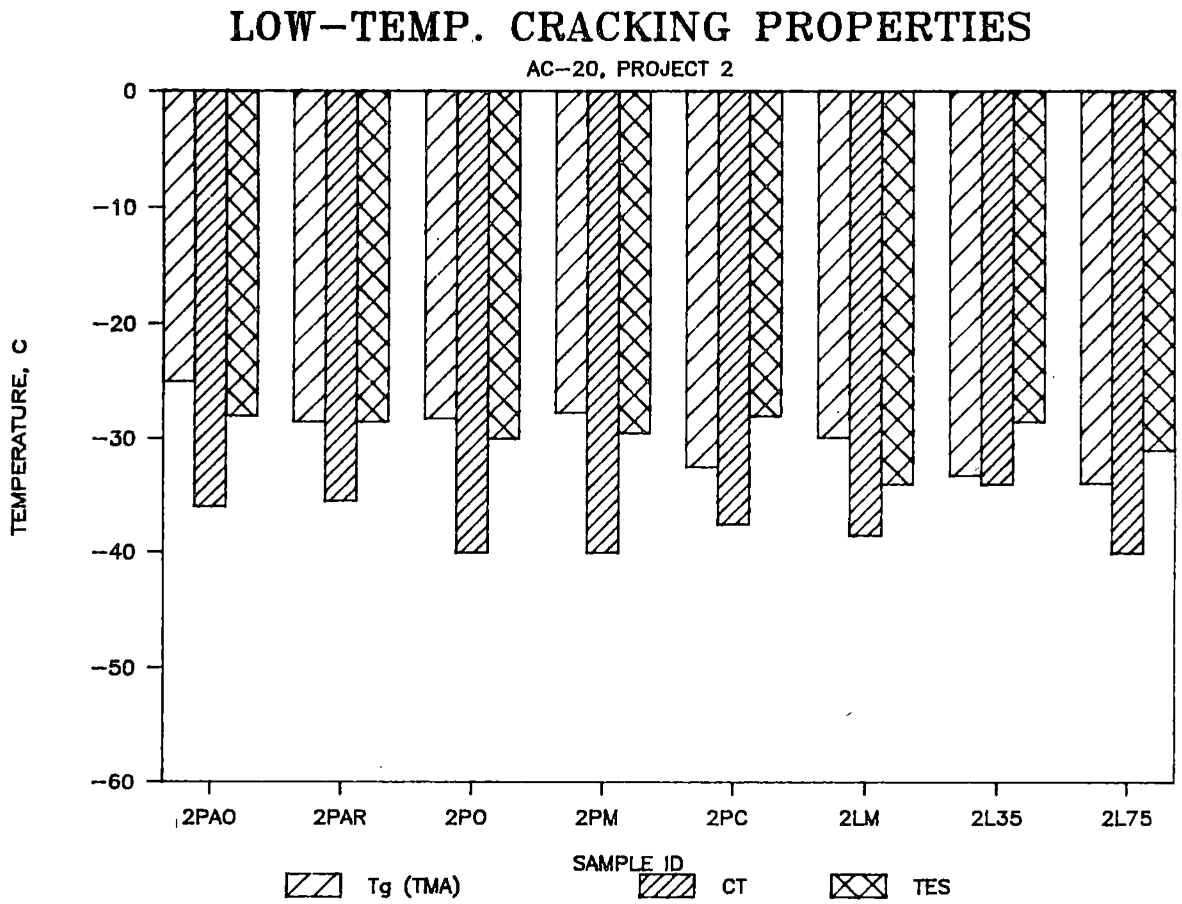

PENETRATION RATIO, P4/P25
AC-20, PROJECT 10 & 12
PENETRATION RATIO
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10PAO 10PAR 10PO 10L35 10L75
12PAO 12PAR 12PO 12L35 12L50 12L75
SAMPLE ID

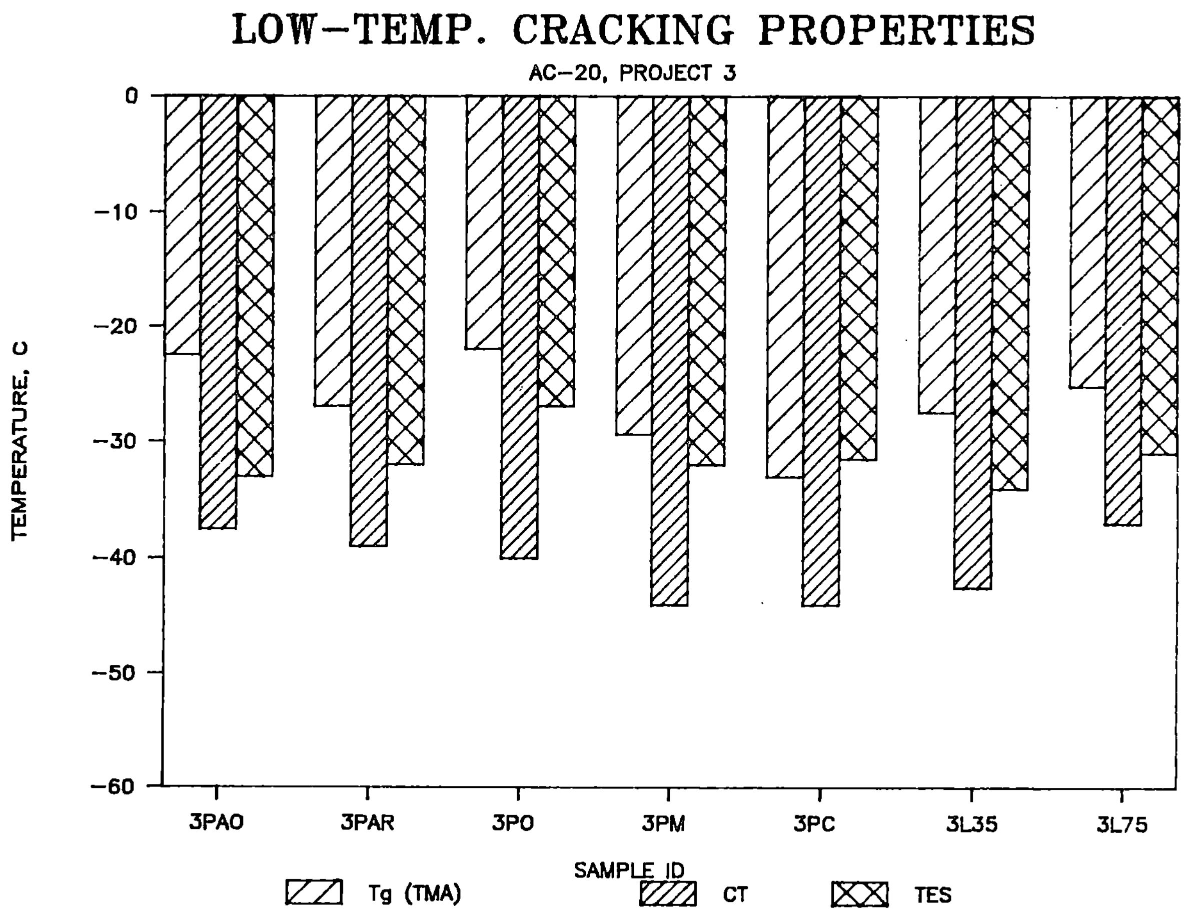

VIS-TEMP SUSCEPTIBILITY
AC-20, PROJECT 2 & 3
VTS
5
4
3
2
1
0
2PAO 2PAR 2PO 2PM 2PC 2LM 2L35 2L75 3PAO 3PAR 3PO 3PM 3PC 3L35 3L75
SAMPLE ID

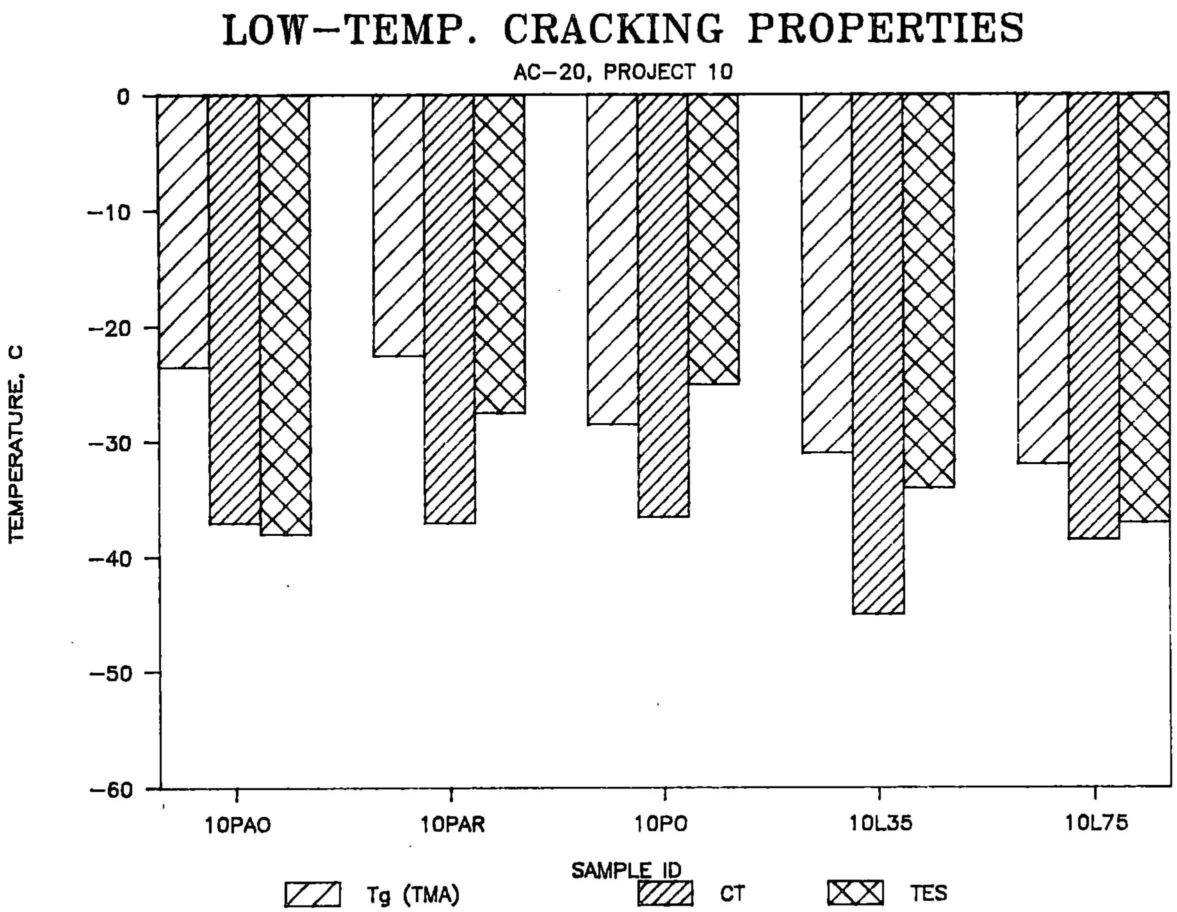

VIS-TEMP SUSCEPTIBILITY
AC-20, PROJECT 10 & 12
VTS
5
4
3
2
1
0
10PAO 10PAR 10PO 10L35 10L75 12PAO 12PAR 12PO 12L35 12L50 12L75
SAMPLE ID

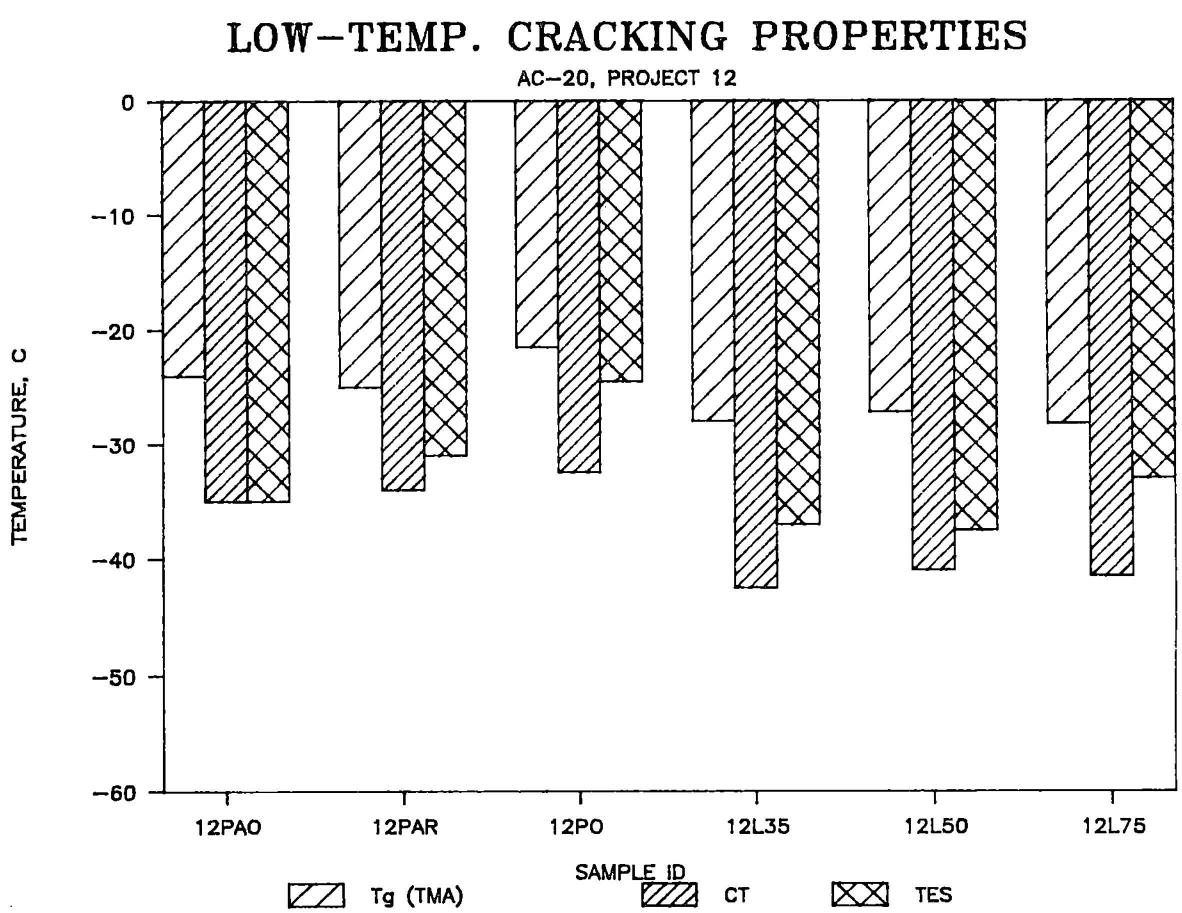

STIFFNESS AT −23 C & −29 C
AC−20, PROJECT 2 & 3
STIFFNESS, ksi
0
2
4
6
8
10
12
14
16
18
20
22
24
26
2PAO
2PAR
2PO
2PM
2PC
2LM
2L35
2L75
3PAO
3PAR
3PO
3PM
3PC
3L35
3L75
SAMPLE ID
S,−23
S,−29


STIFFNESS AT −23 C & −29 C
AC−20, PROJECT 10 & 12
STIFFNESS, ksi
0
2
4
6
8
10
12
14
16
18
20
22
24
26
10PAO
10PAR
10PO
10L35
10L75
12PAO
12PAR
12PO
12L35
12L50
12L75
SAMPLE ID
S,−23
S,−29


LOW-TEMP. CRACKING PROPERTIES
AC-20, PROJECT 2
TEMPERATURE, C
0
-10
-20
-30
-40
-50
-60
2PAO
2PAR
2PO
2PM
2PC
2LM
2L35
2L75
SAMPLE ID
Tg (TMA)
CT
TES

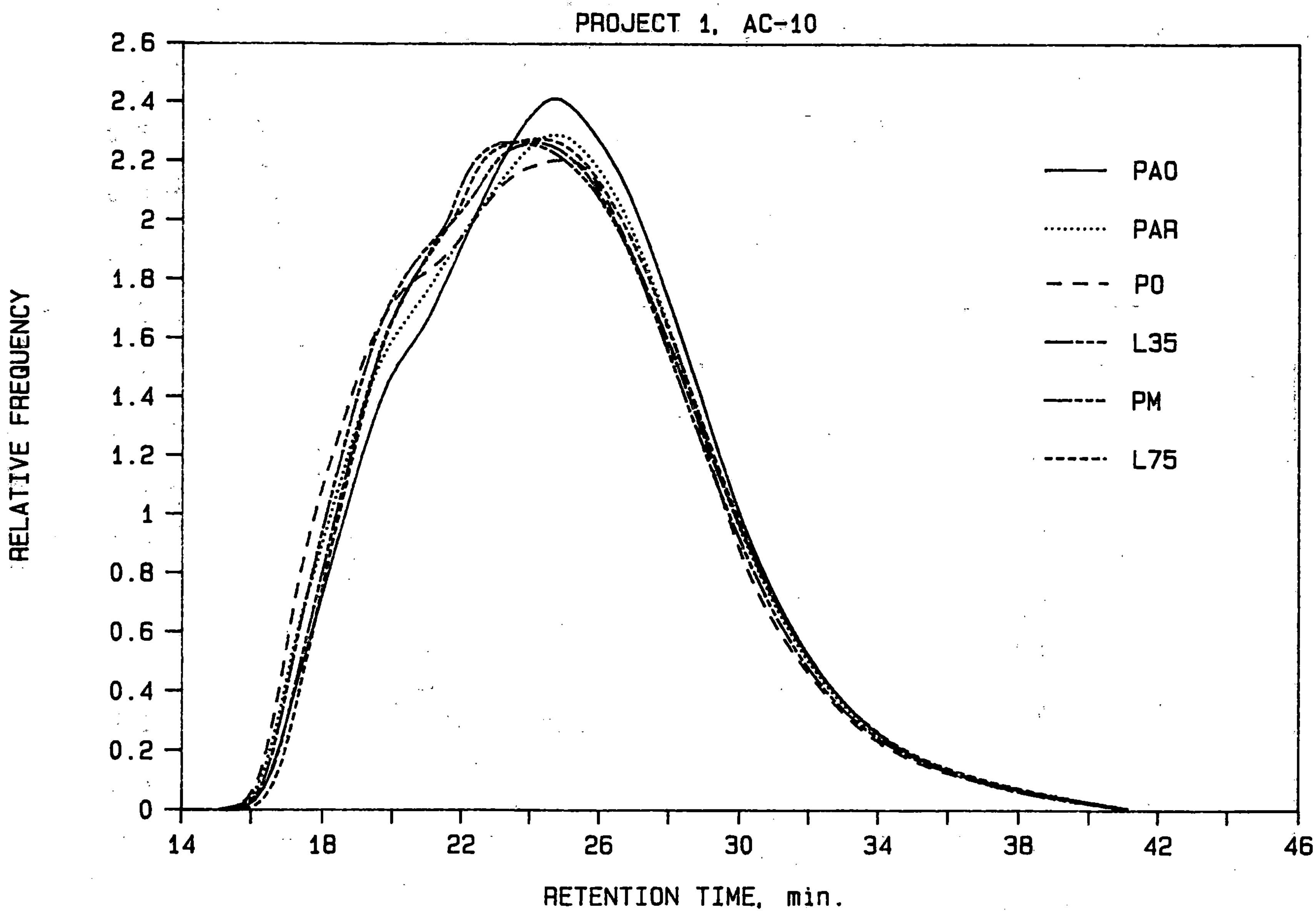

LOW-TEMP. CRACKING PROPERTIES
AC-20, PROJECT 3
TEMPERATURE, C
0
-10
-20
-30
-40
-50
-60
3PAO
3PAR
3PO
3PM
3PC
3L35
3L75
SAMPLE ID
Tg (TMA)
CT
TES

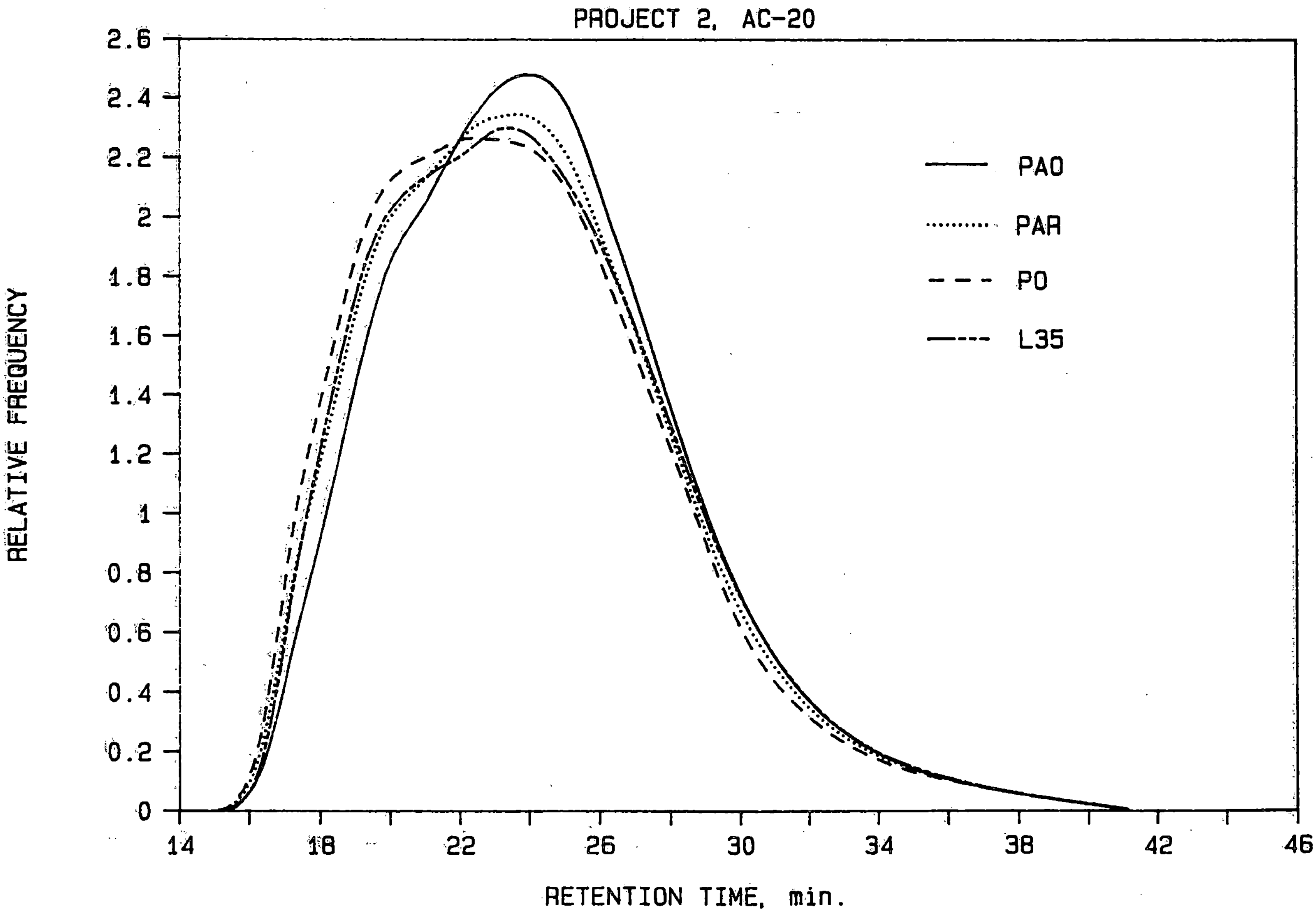

LOW-TEMP. CRACKING PROPERTIES
AC-20, PROJECT 10
TEMPERATURE, C
0
-10
-20
-30
-40
-50
-60
10PAO
10PAR
10PO
10L35
10L75
SAMPLE ID
Tg (TMA)
CT
TES

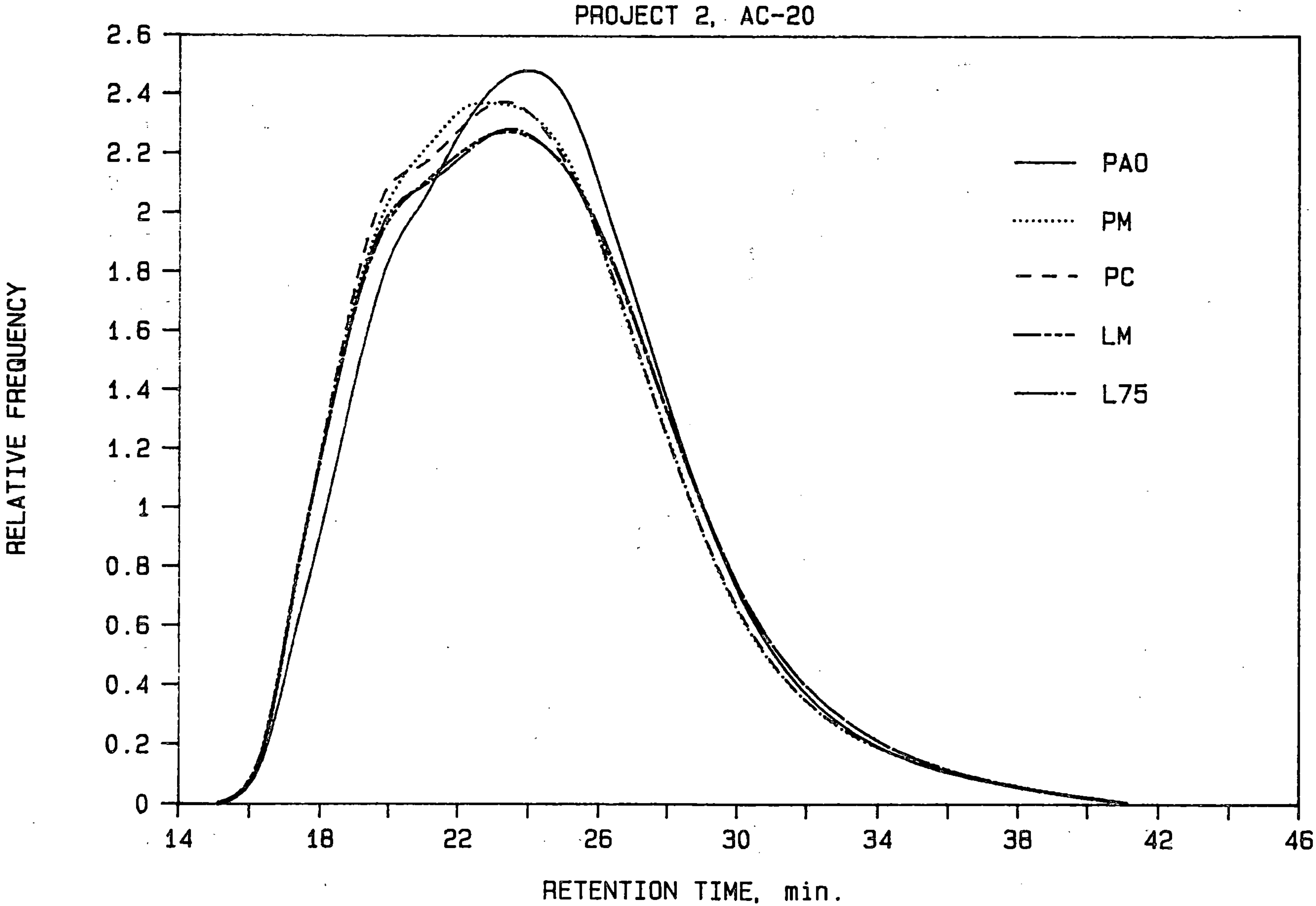

LOW-TEMP. CRACKING PROPERTIES
AC-20, PROJECT 12
TEMPERATURE, C
0
-10
-20
-30
-40
-50
-60
12PAO
12PAR
12PO
12L35
12L50
12L75
SAMPLE ID
Tg (TMA)
CT
TES

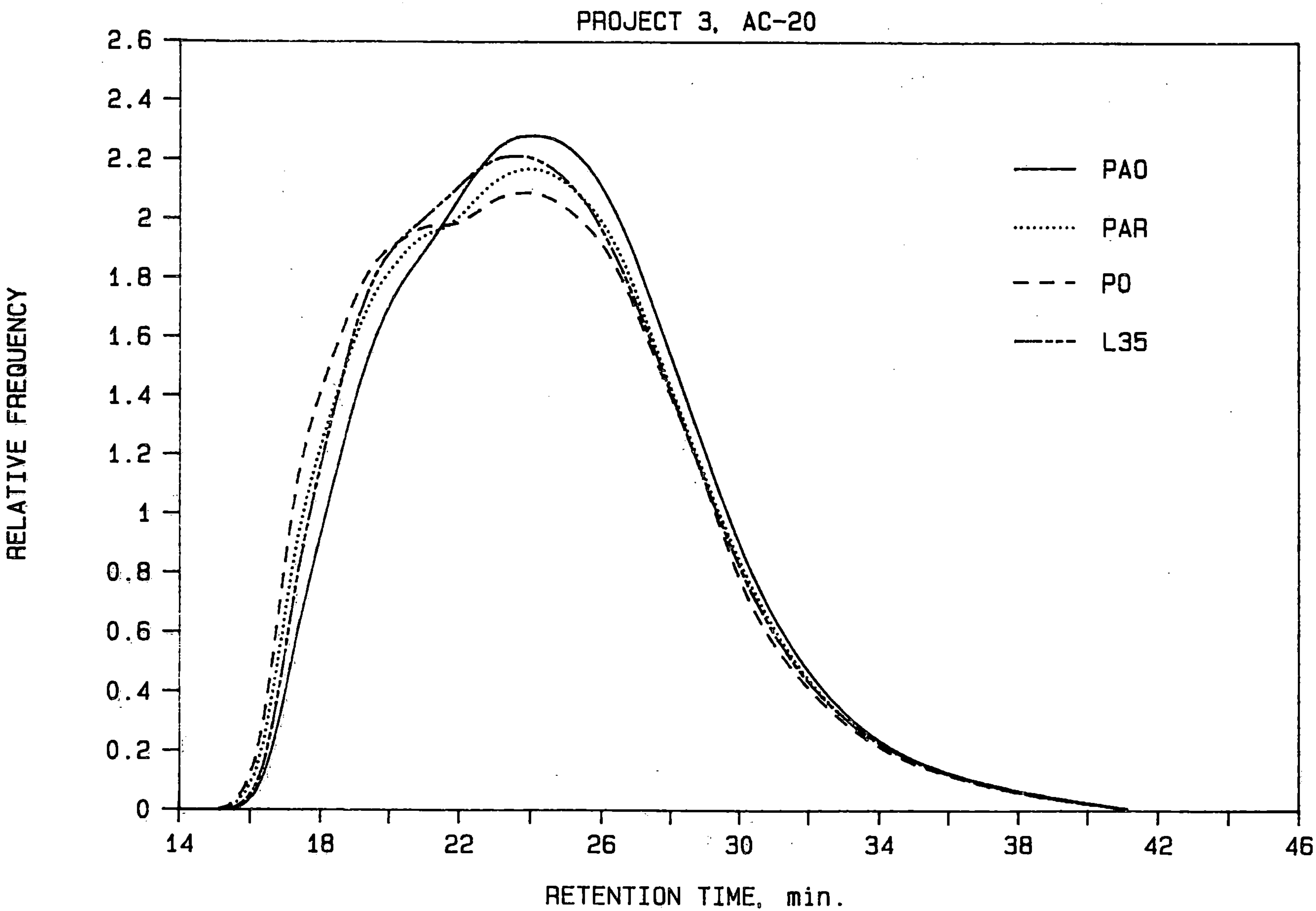
APPENDIX II

HP-GPC Chromatograms.

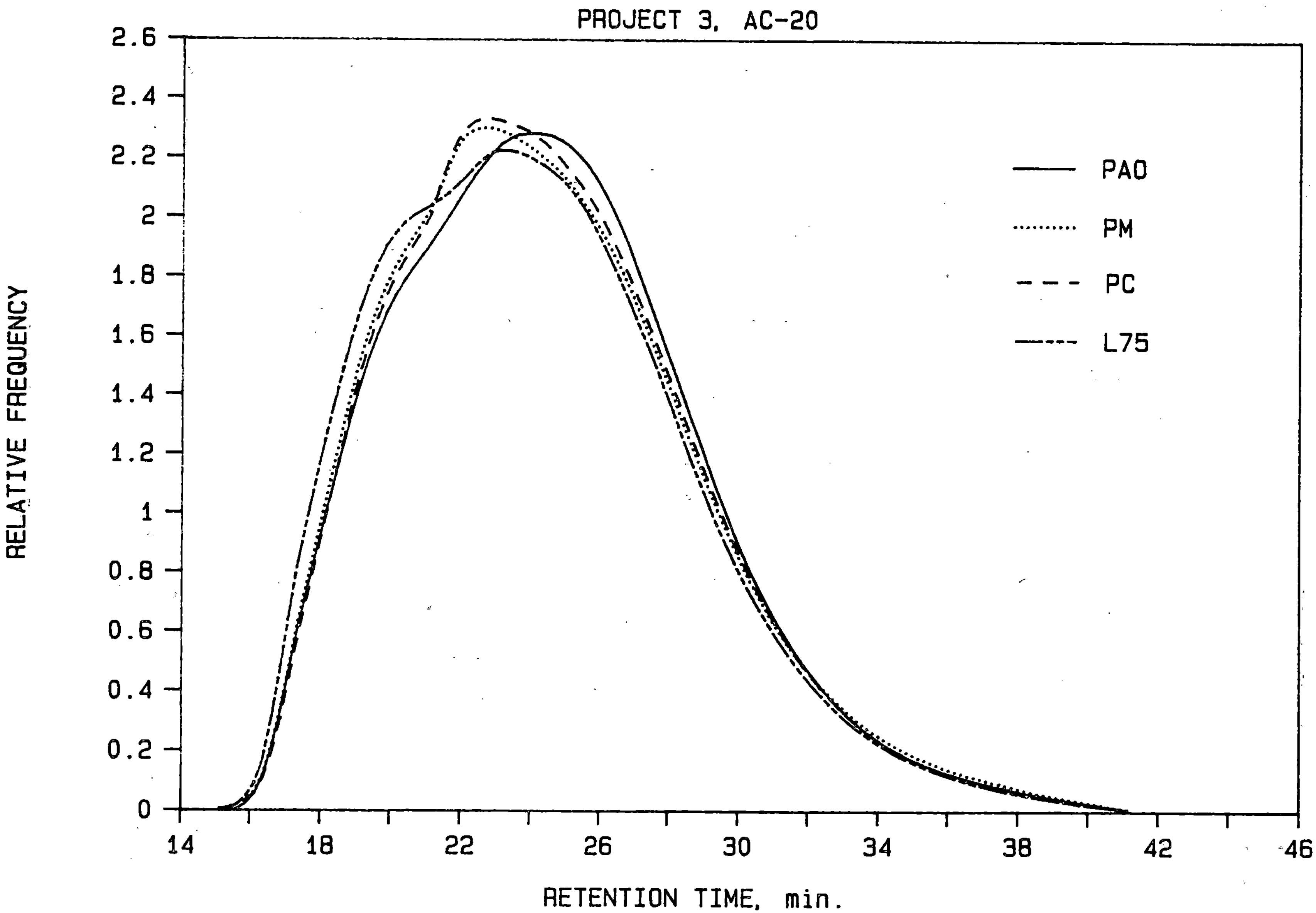

PROJECT 1, AC-10
RELATIVE FREQUENCY
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
18
22
26
30
34
38
42
46
RETENTION TIME, min.
PAO
PAR
PO
L35
PM
L75

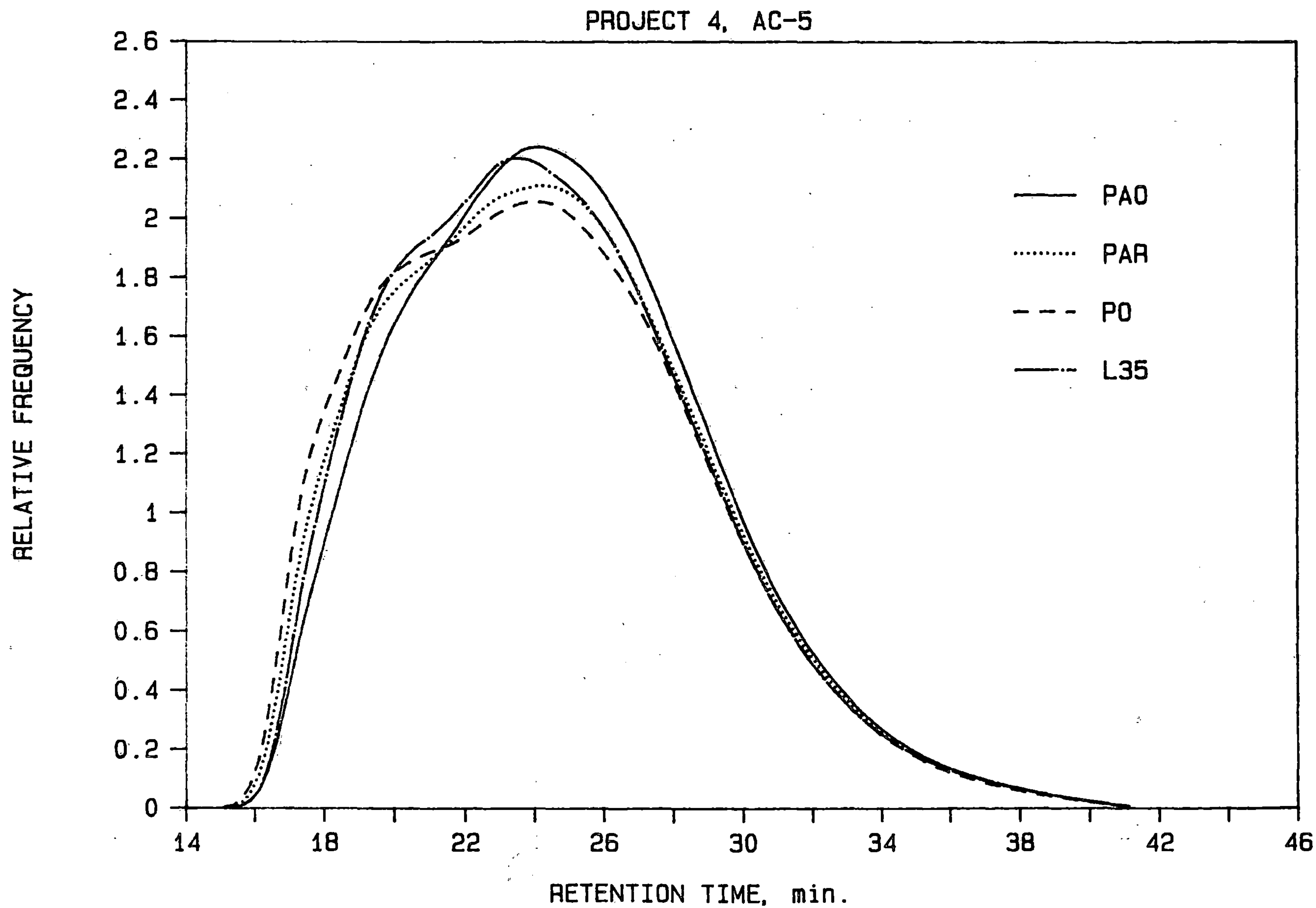

PROJECT 2, AC-20
RELATIVE FREQUENCY
RETENTION TIME, min.
PAO
PAR
PO
L35
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
14
18
22
26
30
34
38
42
46

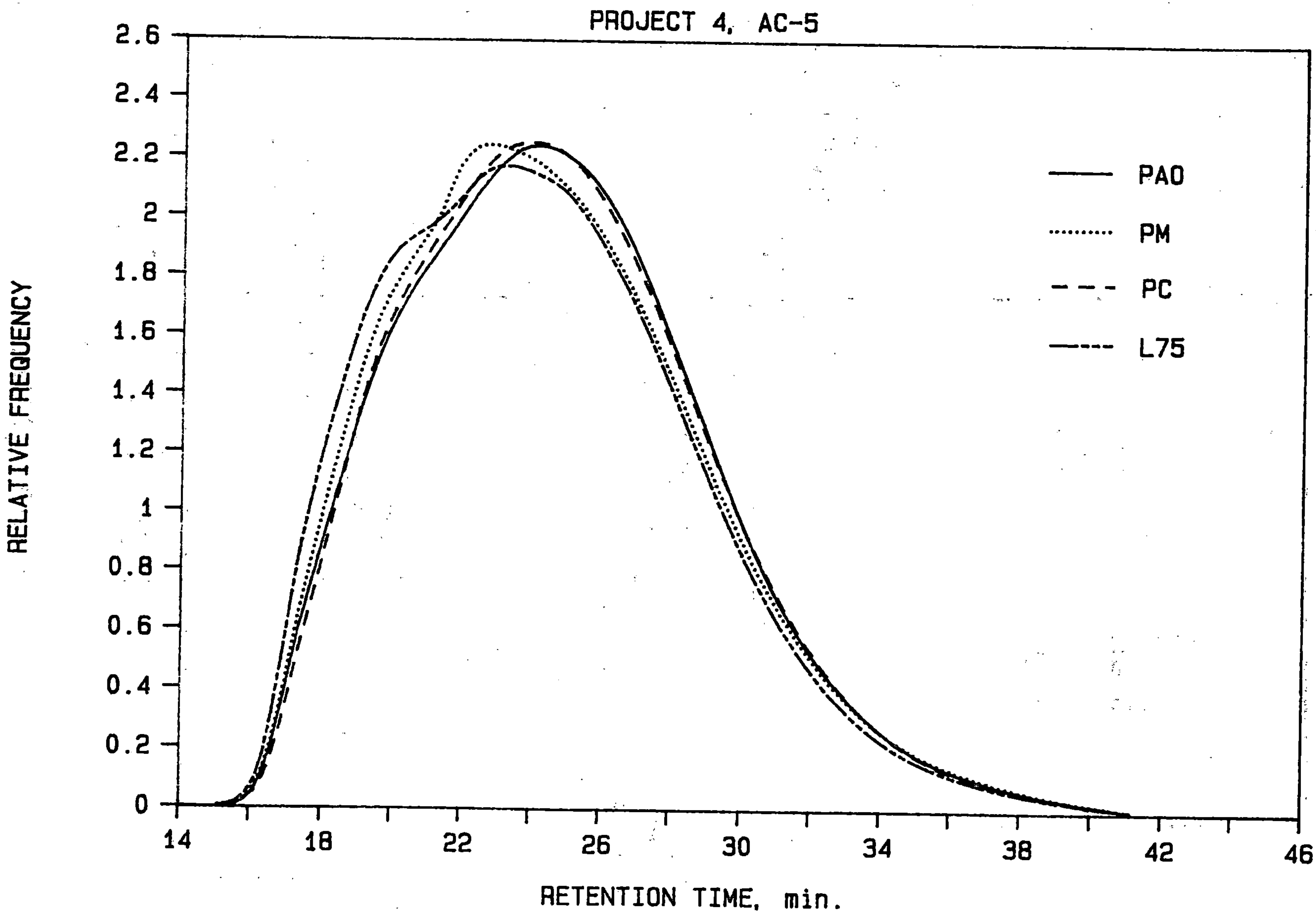

PROJECT 2, AC-20
RELATIVE FREQUENCY
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
18
22
26
30
34
38
42
46
RETENTION TIME, min.
PAO
PM
PC
LM
L75

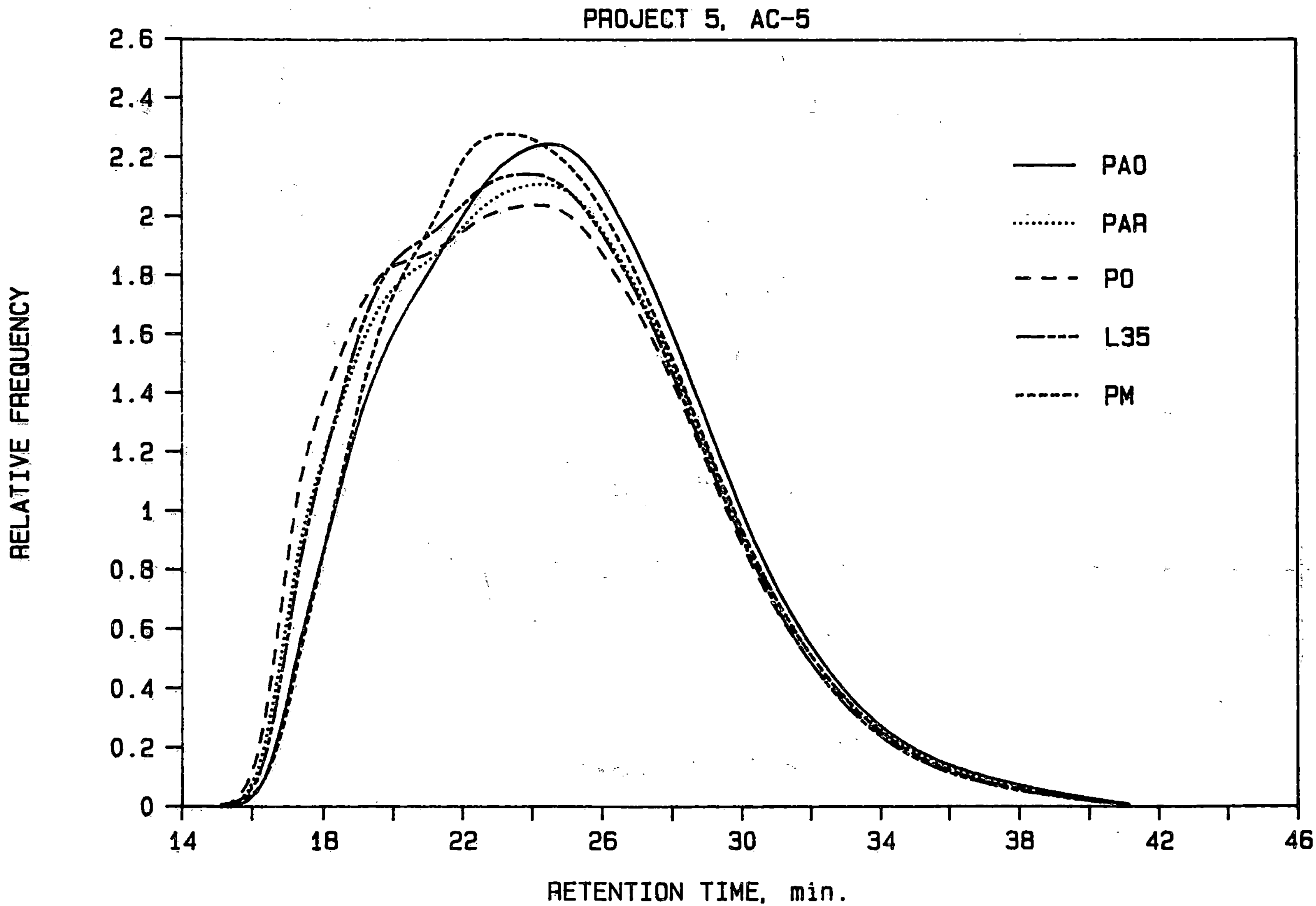


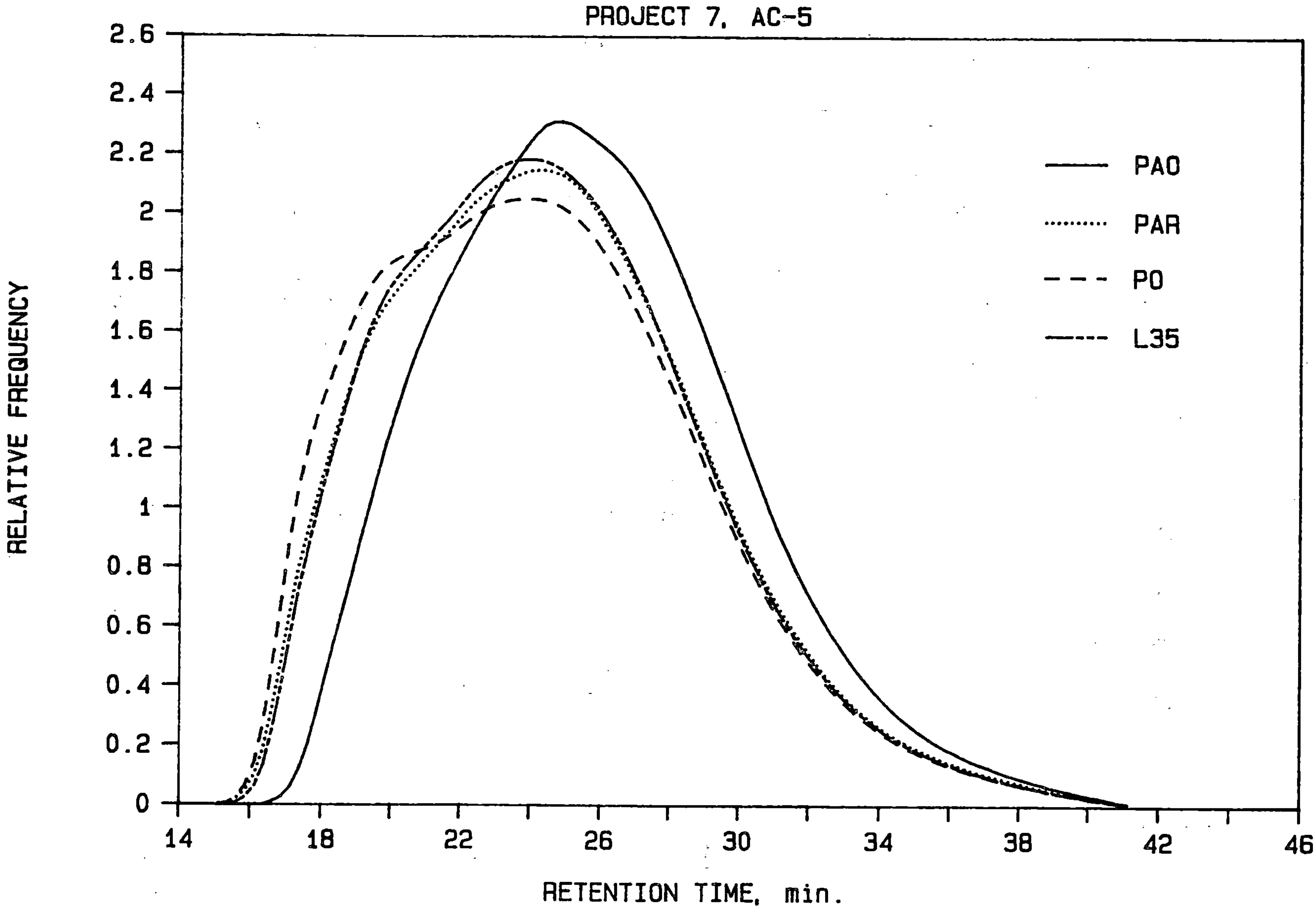
PROJECT 3, AC-20
RELATIVE FREQUENCY
RETENTION TIME, min.
PAO
PAR
PO
L35
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
18
22
26
30
34
38
42
46

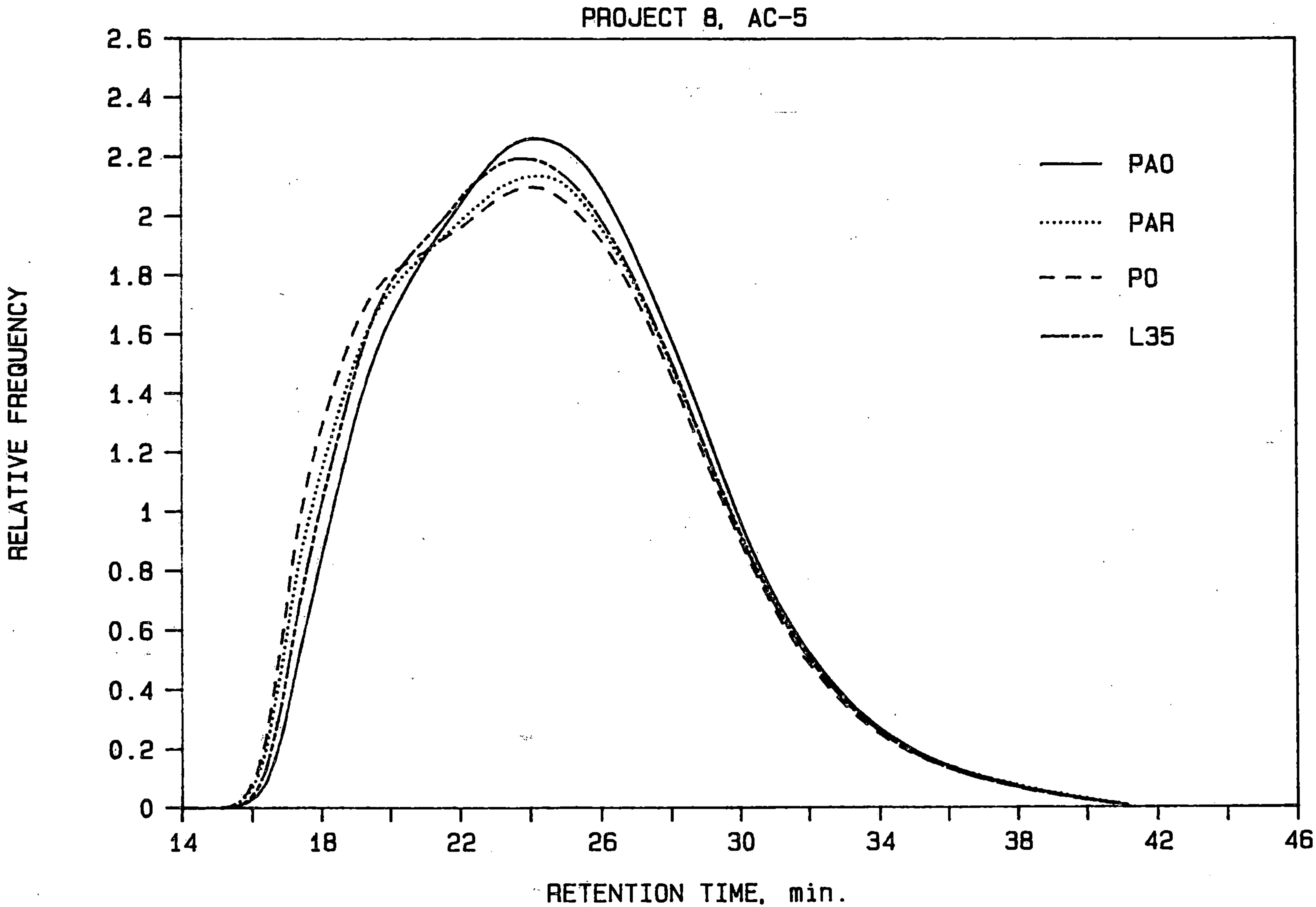

PROJECT 3, AC-20
RELATIVE FREQUENCY
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
18
22
26
30
34
38
42
46
RETENTION TIME, min.
PAO
PM
PC
L75

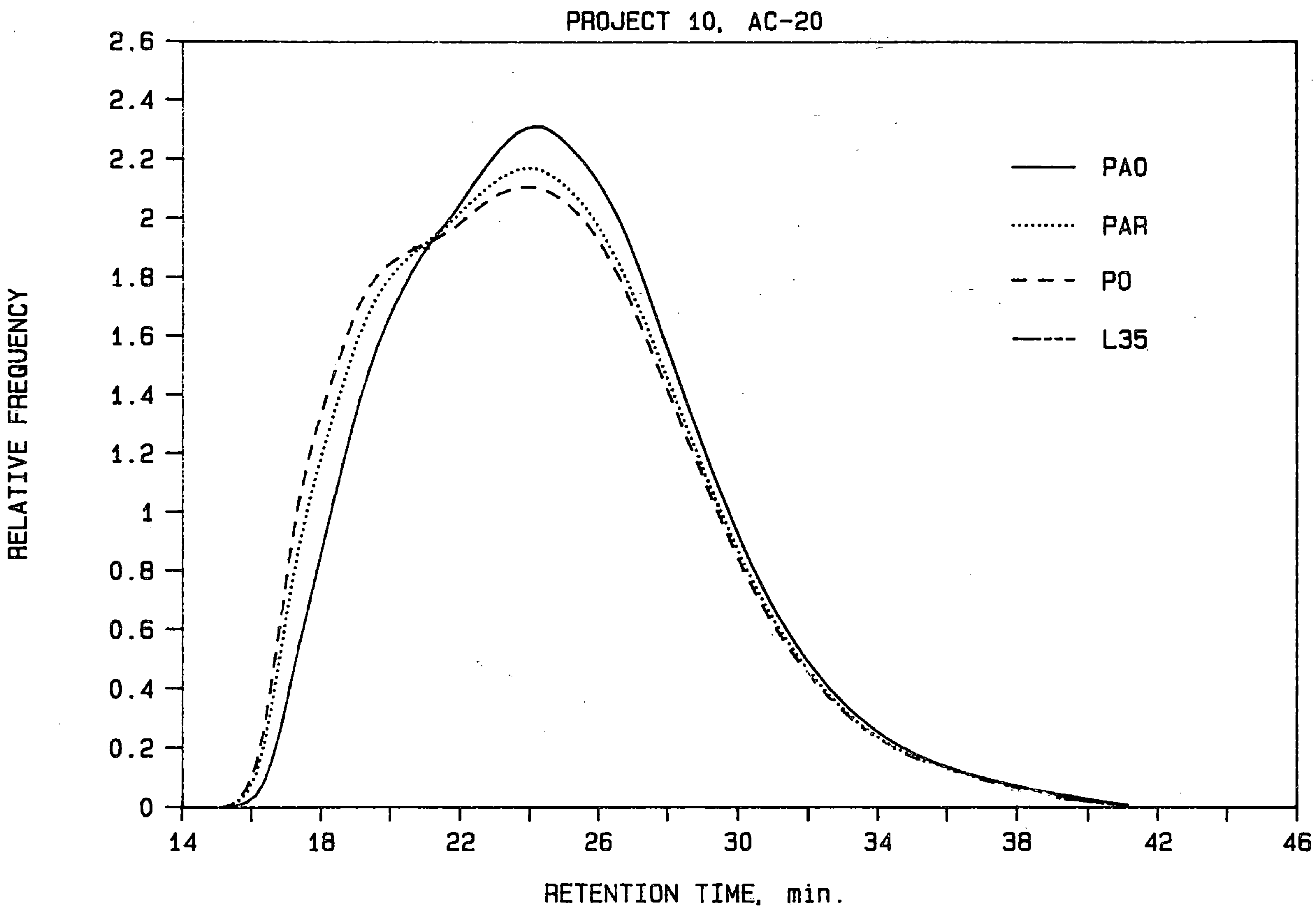

PROJECT 4, AC-5
RELATIVE FREQUENCY
RETENTION TIME, min.
PAO
PAR
PO
L35
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
18
22
26
30
34
38
42
46

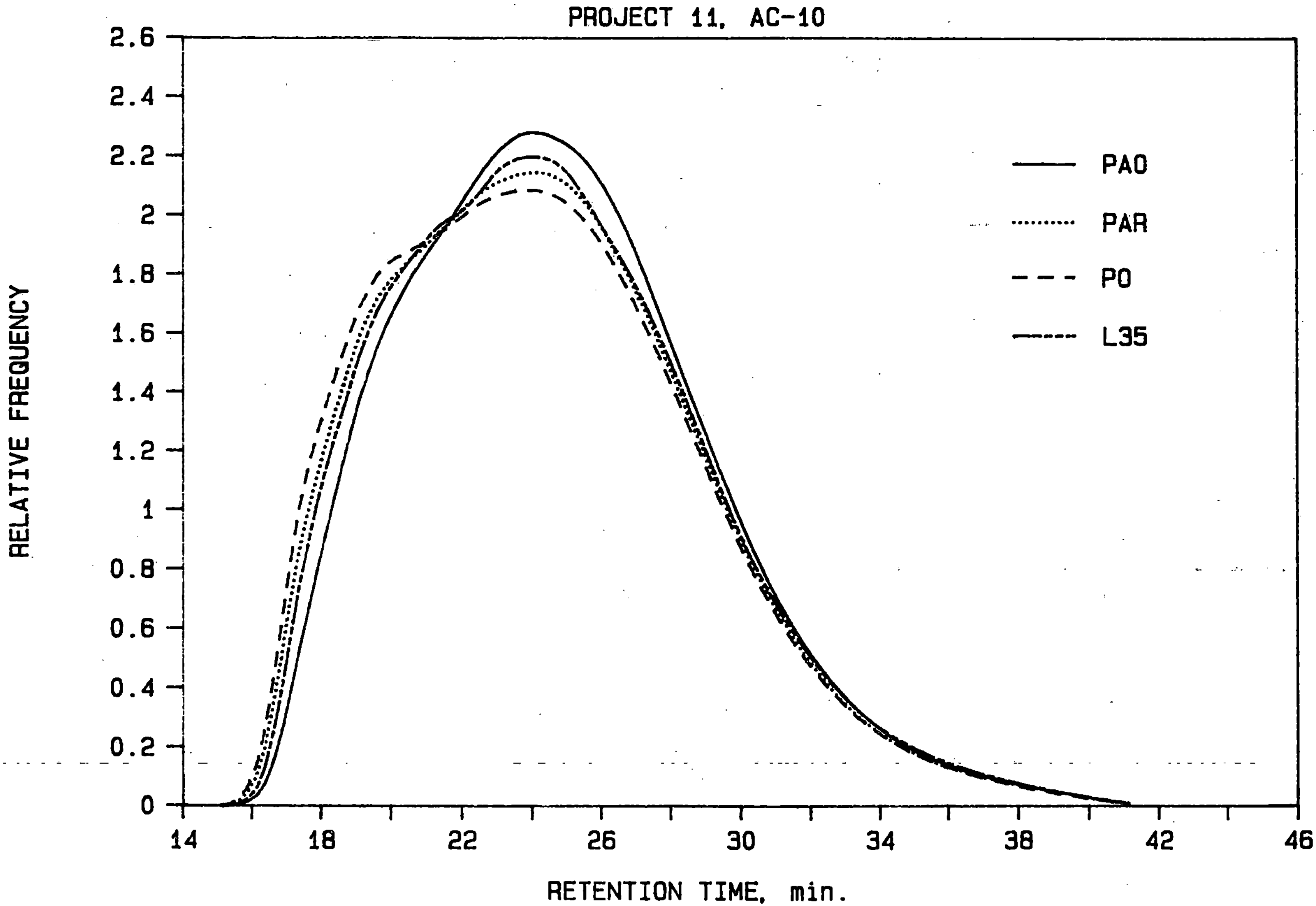

PROJECT 4, AC-5
RELATIVE FREQUENCY
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
18
22
26
30
34
38
42
46
RETENTION TIME, min.
PAO
PM
PC
L75


PROJECT 5, AC-5
RELATIVE FREQUENCY
RETENTION TIME, min.
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
14
18
22
26
30
34
38
42
46
PAO
PAR
PO
L35
PM

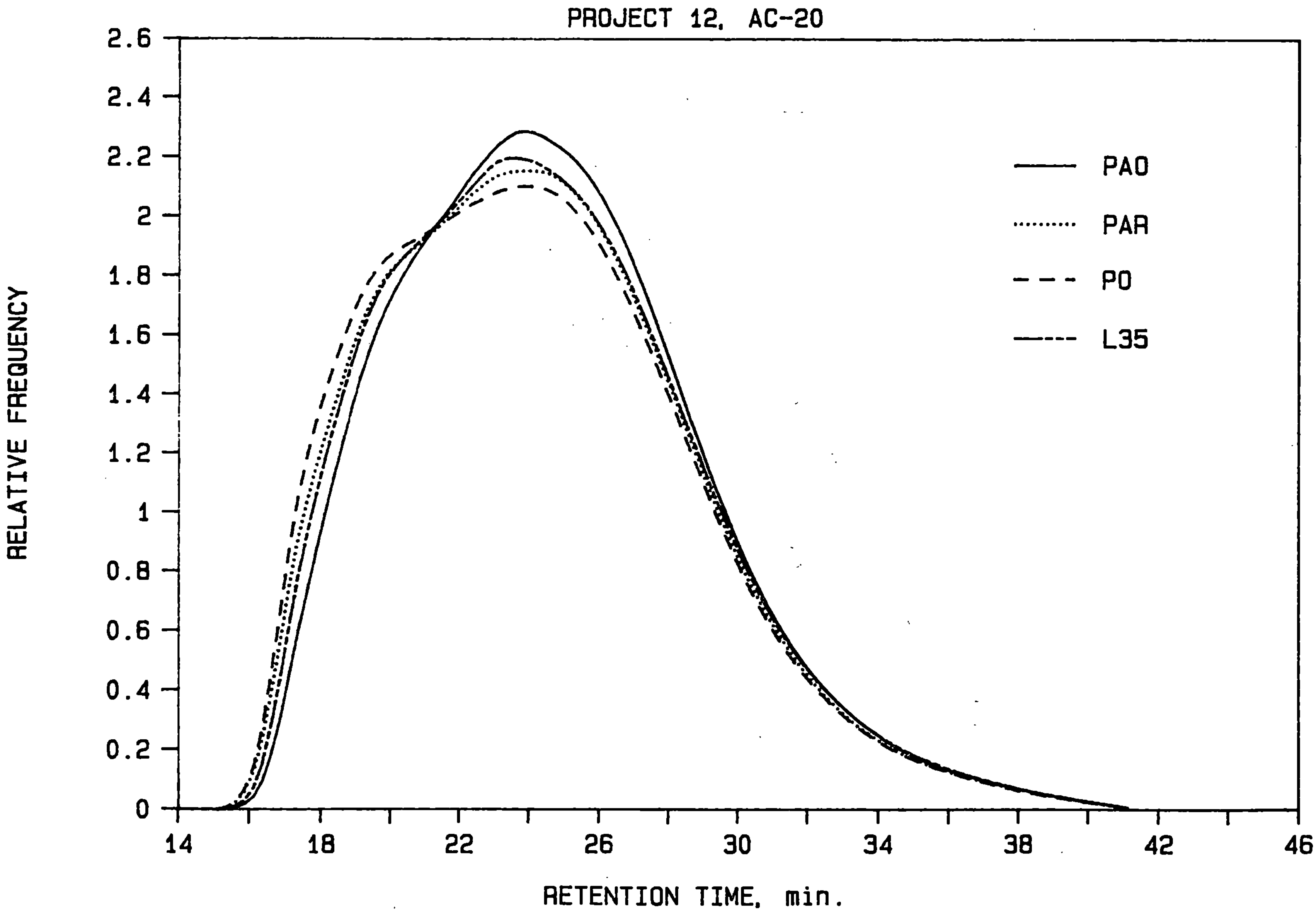

PROJECT 7, AC-5
RELATIVE FREQUENCY
RETENTION TIME, min.
PAO
PAR
PO
L35
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
14
18
22
26
30
34
38
42
46


PROJECT 8, AC-5
RELATIVE FREQUENCY
RETENTION TIME, min.
PAO
PAR
PO
L35
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
14
18
22
26
30
34
38
42
46


PROJECT 10, AC-20
RELATIVE FREQUENCY
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
18
22
26
30
34
38
42
46
RETENTION TIME, min.
PAO
PAR
PO
L35



PROJECT 11, AC-10
RELATIVE FREQUENCY
RETENTION TIME, min.
PAO
PAR
PO
L35
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
14
18
22
26
30
34
38
42
46



PROJECT 12, AC-20
RELATIVE FREQUENCY
RETENTION TIME, min.
PAO
PAR
PO
L35
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
18
22
26
30
34
38
42
46