EVALUATION OF AN OPTIMUM ASPHALT CONCRETE MIX DESIGN USING FRACTURE MECHANICS PRINCIPLES

by

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Submitted in Partial Fulfillment of the Requirements of the
University Undergraduate Fellows Program

1985-86

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April 1986

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ABSTRACT

Limitations of current testing procedures for asphalt concrete, asphalt additives, and alternative binders have made necessary a more theoretical basis for testing procedures. A new parameter, Marshall Toughness, is formulated in this paper and its relevance for determining the optimum asphalt content of a mix design is explored.

ACKNOWLEDGEMENTS

I wish to express my thanks to Dr. Don Saylak for his help and support through this project. His enthusiasm and interest in his work have inspired me and opened a new world to me.

I also wish to thanks all my teachers for providing lessons never to be forgotten.

Finally, I wish to thank my family and friends for supporting me in my efforts to acquire an education.

DEDICATION

To my parents with love, for teaching me never
to quit and always to give my best effort.

INTRODUCTION

NATURE OF THE PROBLEM

The development and subsequent popularity of the automobile early in the 20th century led to public demands for improved road surfaces. Flexible pavements constructed with asphalt cement binders proved to be inexpensive and fairly durable. A methodical procedure for formulating and evaluating the performance of these pavements was necessary. The Marshall Method of Mix Design was developed in the 1930's as a means to predict the optimum asphalt content for an asphalt concrete pavement. Today, this test remains one of the primary methods of mix design in the pavement industry. The Marshall method provides acceptable results for conventional asphalt concrete mixtures when correlated to data that has been compiled for decades.*

However, the advent of asphalt additives and alternative binders in the 1970's resulted in materials with unfamilar or unknown material properties. Little data was available for designing mixes with the altered binders. New tests had to be developed or old tests modified to accomodate the changing materials. The usage of asphalt additives and alternative binders in recent years has generated a need for more theoretical tests that quantify basic material properties.

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* This paper follows the format of the American Society of Civil Engineers *Journal of Materials Engineering*.

OBJECTIVES

The objective of this research is to determine the relevance of a "Marshall Toughness" parameter as a tool for generating optimum asphalt concrete mix designs using fracture mechanics principles. Fracture mechanics deals with stress concentrations in a fractured, or cracked, material. This was accompolished by dividing the research into three phases with objectives for each phase. The first phase objective was to develop a single parameter, Marshall Toughness, that could be used to refine or enhance the existing Marshall Method. The second phase consisted of a comparison of the conventional Marshall optimum asphalt content to the Marshall Toughness optimum asphalt content. The objective of the third phase was to determine which of the two optimum asphalt contents would yield a pavement with better characterisitics and performance.

LITERATURE REVIEW

MARSHALL METHOD

The Marshall Test method was considered to be the standard for comparison in this research because of widespread its usage by many state highway departments.The Marshall method of mix design optimizes asphalt concrete mixtures through trade-offs on structural properties such as stability, flow, percent voids, unit weight, and voids in the mineral aggregate (VMA). Figure 1 shows a graphical example of the data generated by the Marshall procedure.

Procedure.- The Marshall procedure begins with the preparation of the test specimens. Three or five specimens are prepared for each combination of asphalt content and aggregate. The aggregates are dried and heated, then mixed with separately heated asphalt. The mixture is then compacted in a mold by use of a compaction hammer meeting ASTM specifications. Compaction is according to traffic design category (light, medium, or heavy). After the specimens have cooled to room temperature, usuallly overnight, bulk specific gravity is determined. Stability and flow are measured by testing in a Marshall testing apparatus (See Figure 2). Stability is measured as the total load in pounds to produce failure of the specimen. Stability refers to the ability of a pavement to resist deformation under application of loads. Flow is a measure of strain; it is the amount of deformation in inches to the point of failure. A density and voids analysis is performed using bulk specific gravity. The set of test property curves is plotted, and an optimum asphalt content is obtained according to Marshall

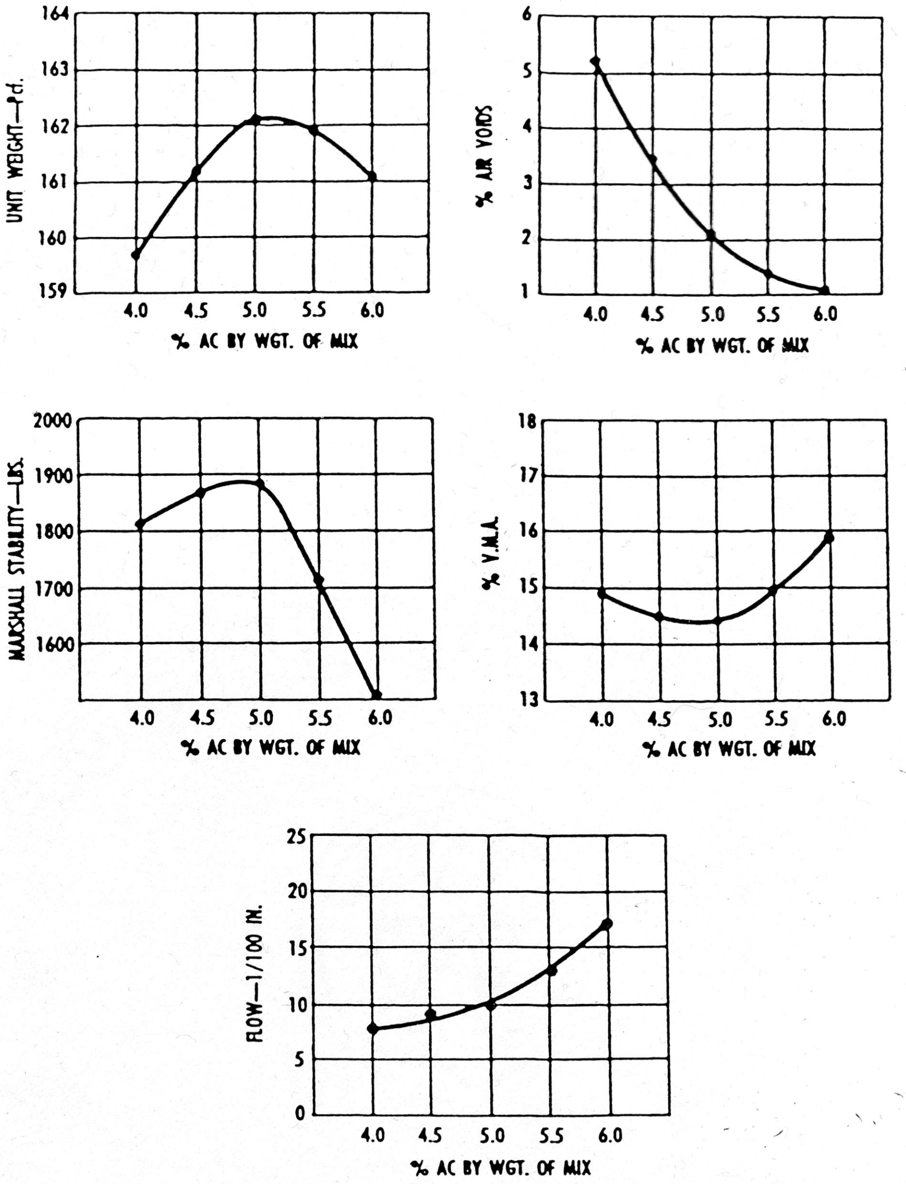

Figure 1. Marshall Test Property Curves

labels

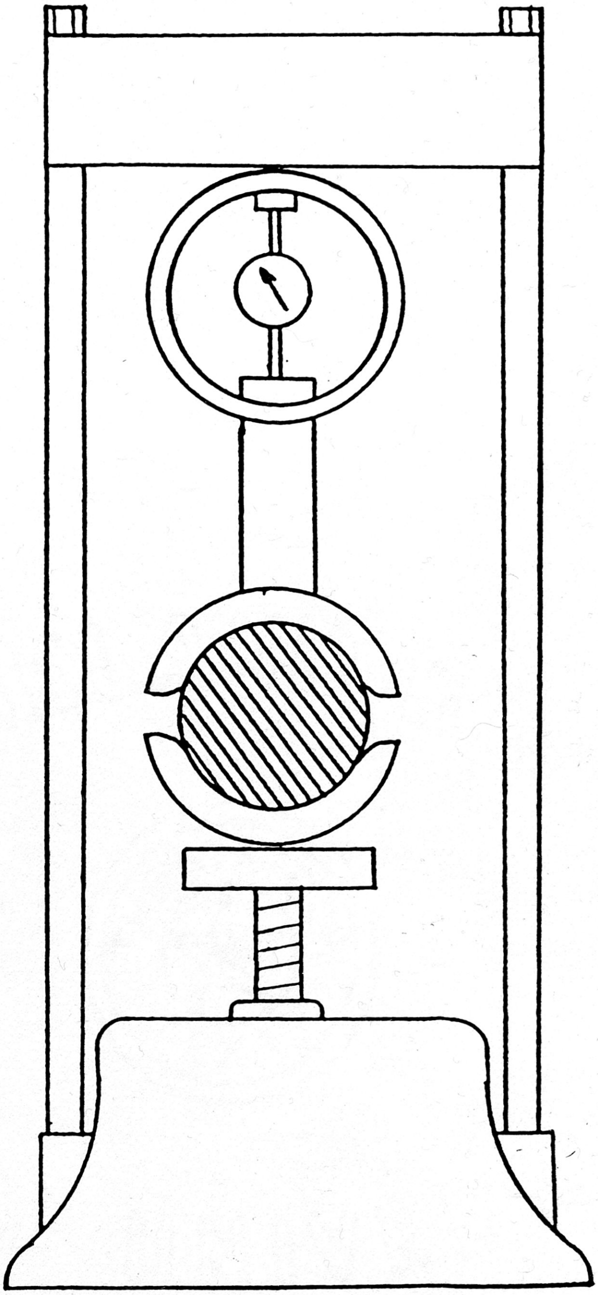

Figure 2. Marshall Testing Apparatus

design criteria.(4) For exact specifications, see Reference (5).

Limitations.- The Marshall test is qualitative in nature, providing a reliable basis for asphalt concrete mix design primarily because of the enormous amount of data and field experience amassed over several decades. The development of a more theoretical basis for asphalt concrete mix could offer several advantages by quantifying these asphalt concrete properties to enhance the predictability of pavement cracking.

THEORY OF THE TOUGHNESS PARAMETER

Toughness is defined as the ability of a material to absorb large amounts of energy.(1) Toughness is measured by the energy required to fracture a specimen. For the purposes of this research, toughness was measured graphically as the area under the stability-flow curve up to the point of failure. Toughness fails to give a quantitative measure of the material's physical properties, but it does provide a good basis for qualitative comparisons. Mix design using different binders and aggregates can be compared on the basis of toughness.

THEORY OF THE FAILURE ENVELOPE

A failure envelope is the curve drawn through the failure points of a material tested at varying temperatures and strain rates. An example of a failure envelope as presented by Smith (6) for an ideal elastomer is shown in Figure 3. Smith's failure envelope yields a basic chacterization of the ultimate tensile properties of a linear viscoelastic material. Work by Finn (2) concluded that for short loading times (such as the Marshall Test) asphalt concrete behaves essentially as a linear viscoelastic material. The failure envelope for an asphalt concrete mix design produced by Little and Richey (3) has the same shape as the upper half of the envelope presented by Smith. Despite the fact that the asphalt concrete failure envelope does not appear exactly as predicted by Smith, the failure envelope concept is applicable to evaluating the response of a range of materials over a range of temperatures or loading times.

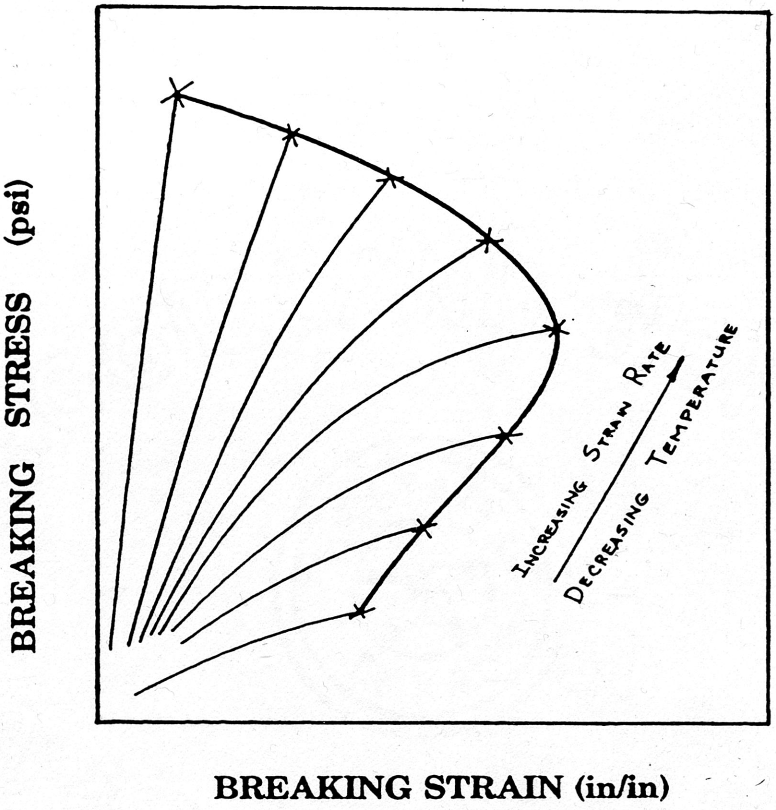

Figure 3. Smith's Chacterization of Elastomer Ultimate Tensile Properties (from Smith (6))

METHODS AND GENERAL PROCEDURE

The data necessary for this analysis was drawn from two related research projects of the Texas State Highway Department currently in progress. The testing for the projects encompasses a variety of mix designs including asphalt concrete, asphalt additives and alternative binders. Testing on the projects included measuring Marshall stability and flow, modulus of resilience, and indirect tension tests.

MARSHALL TOUGHNESS PARAMETER

The method of analysis proposed for study in this project was the development of a "Marshall Toughness" parameter. This parameter allowed the use of a single parameter for selection of an optimum asphalt content, rather than attempting to balance several dissimilar comparisons as does the Marshall test. Stability and flow data recorded graphically during the Marshall tests produces a curve that has a shape as shown in Figure 4. Toughness is a measure of energy required to cause failure. The Marshall Toughness parameter graphically integrates the area under this curve up to the maximum stability and reports this area as "Marshall Toughness".

COMPARISON OF OPTIMUMS

The optimum asphalt content predicted by the Marshall Toughness method was compared with the optimum given by conventional Marshall testing. The conventional Marshall optimum was obtained by plotting stability versus percent asphalt content, fitting a curve to the points, then reading the asphalt content at maximum stability. The Marshall Toughness optimum was obtained in the same way. Figure 5 shows a sample diagram

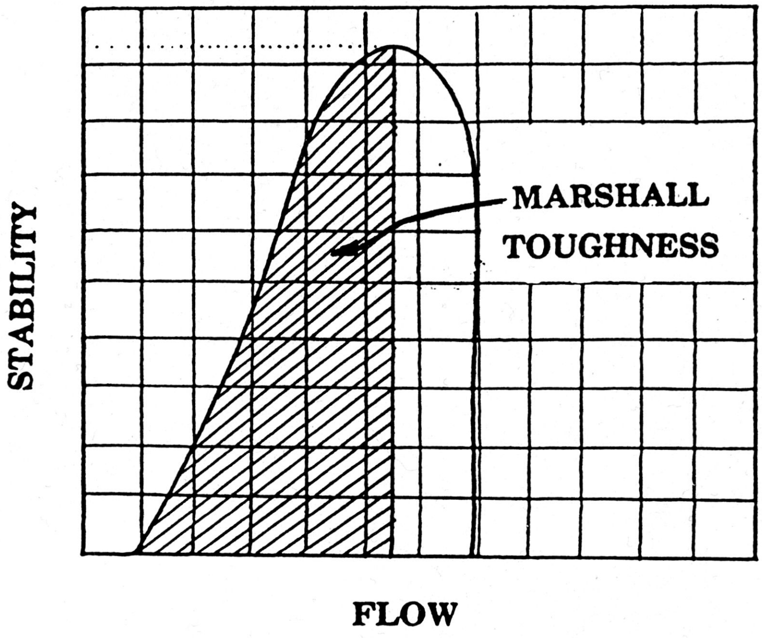

Figure 4. Typical Marshall Curve

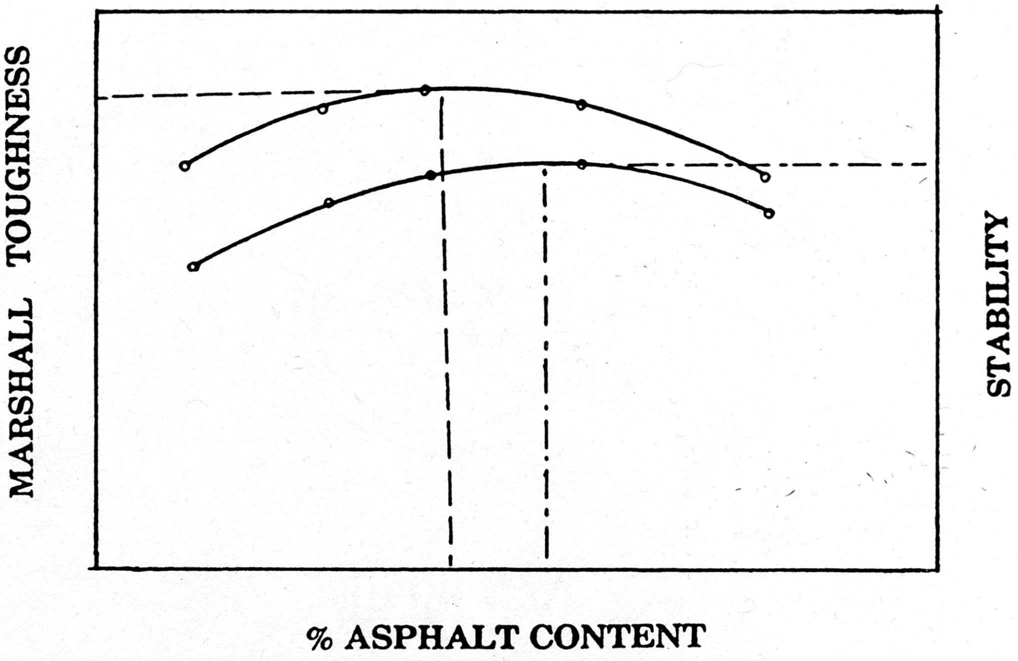

Figure 5. Determination of Optimum Asphalt Content

of this procedure.

FAILURE ENVELOPE ANALYSIS

To determine which method better predicts the fracture potential of the mix design, a failure envelope was to be developed and compared for the two optimums. A failure envelope was observed earlier in this report and was considered in this research as the best-fit curve drawn through the failure points of specimens tested at varying strain rates and temperatures. The failure envelope that contains a greater area under the curve will yield a mix design that performs better over a greater range of conditions.

A lack of time and financial resources precluded the development of a failure envelope especially for this project. However, the work done by Little and Richey yielded consistent results for asphalt concrete and Sulphlex (an alternative binder) failure envelopes. An increase in binder content produced a shift in the failure envelope upward and to the right as shown in Figure 6.

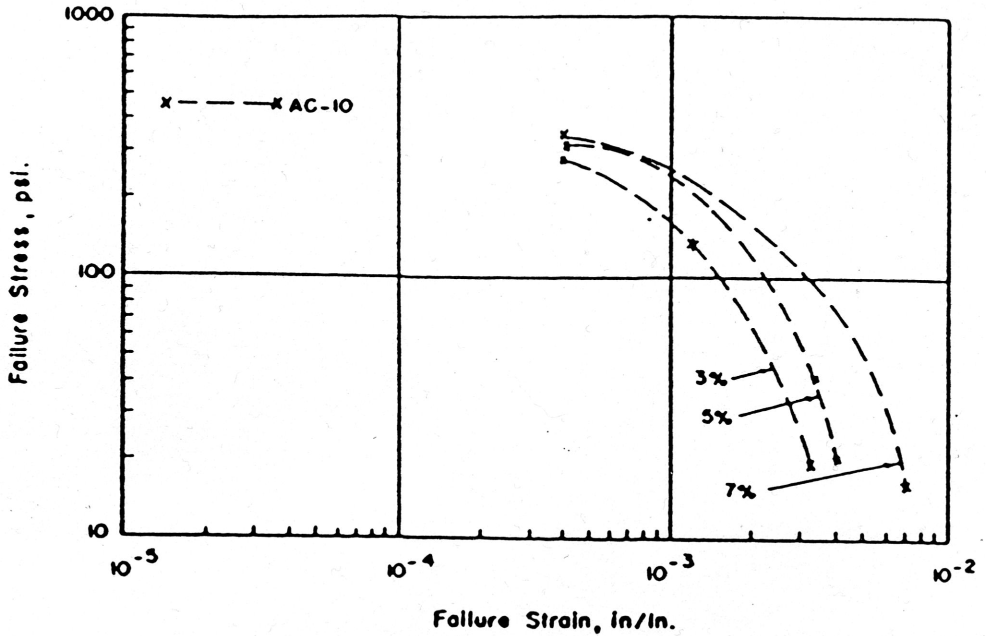

Figure 6. Shift in the Failure Envelope with a Change in Binder Content

RESULTS

The development of the Marshall Toughness parameter was successful by approximation. The original graphical data necessary for developing the graphical integration of Marshall Toughness was unavailable. Other data was analyzed to determine the accuracy of the triangular approximation. Triangular approximation consistently gave values lower than the actual integration of the Marshall Toughness area. Results for the development of the Marshall Toughness approximation are contained in the calculations included in Appendix 2.

The results of the comparison of optimum asphalt content are presented in Table 1. Data from nine different mix designs, representing a broad spectrum of behavior, were analyzed. The general trend in analysis of the data seemed to indicate that an increase in asphalt content is warranted.

As stated before, a failure envelope was not developed solely for this project. Previous work on the topic indicates a consistent shift of the failure envelope upward and to the right with increased binder content, implying improved performance with increased binder content.

Mix Design	Optimum Asphalt Content		% More Asphalt for Marshall Toughness Method
	Conventional Marshall Method	Marshall Toughness Approximation	
TAC10PEA	4.80%	5.15%	0.35
TAC10CRL	4.10%	4.50%	0.40
TAC20RG	3.90%	4.10%	0.20
TAC10RG	4.80%	5.50%	0.70
TAC5RG	5.15%	5.15%	0.00
TAC5RG+LATEX	5.25%	5.65%	0.40
TAC10RG+CARBON BLACK	3.90%	4.10%	0.20
KRATON RG	4.00%	4.10%	0.10
NOVOPHALT RG	4.45%	4.60%	0.15
			Avg = 0.28%

Table 1. Results for Comparison of Optimum Asphalt Contents

DISCUSSION

The results obtained for the approximated Marshall Toughness parameter suggest that an adjustment of the coefficient may give somewhat more accurate results. A coefficient of 0.55, for example, may in reality be closer to the actual value of Marshall Toughness.

Comparison of the optimum asphalt contents indicated that increased asphalt content for most of these mix designs would be appropriate. This implication has several ramifications. To begin with, under-asphalting of a sizable portion of the nation's highways may have resulted. Low asphalt content in pavement can lead to a host of problems. Reduced durability problems such as stripping, ravelling, oxidation, and excessive hardening may be partially caused by low asphalt content. Flexibility of the road may be reduced. Increased asphalt content also signifies increased cost for the same volume of pavement. An increase of 0.3 percent asphalt content of mix designs would be necessary on the average, which translates to roughly 6 percent more asphalt. The additional cost of the pavement initially may be well- invested in terms of reduced maintainance and longer life.

The method used for obtaining the optimum asphalt contents needs further refinement. The asphalt contents selected as optimum were sensitive to changes in the curve plotted through the Marshall Toughness values. More samples may be necessary for complete definition of the curve, although current practice has shown that increments of 0.5 percent asphalt content to be adequate.

SUMMARY AND CONCLUSIONS

The Marshall test gives acceptable results for mix designs, but yields no information on fundamental material properties of asphalt concrete. Results are more empirical than theoretical and must be correlated to pavement performance by use of data compiled over several decades of testing. The proposed enhancement of the Marshall test allows a more theoretical basis for testing. An increase in asphalt content is warranted by results of this project. Further aggressive, in-depth research should refine the Marshall Toughness parameter while supporting the conclusions of this paper.

In reviewing the objective of this set at the beginning of this project, the results obtained were excellent. Each objective was met either through analysis of existing data or through review of related work. Pursuit of this topic in order to further refine the results and procedure is necessary prior to the institution of this method in general practice.

APPENDIX 1 -- REFERENCES

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APPENDIX 2 -- PRESENTATION OF DATA AND CALCULATIONS

LIZ METTING

Date 10/22/85

DATA REDUCTION FORM

APPROXIMATION

Mix Design Texaco AC10

AGGREGATE: PEA GRAVEL

Sample #		Stability	Flow
% Asphalt		lbs.	.01 inch
3.5	a	1050	4.5
	b	1150	4.5
	c	1144	4.2
4.0	a	1014	4.5
	b	1139	4.1
	c	1144	4.5
4.5	a	1050	5
	b	1082	4.5
	c	1046	4.5
5.0	a	1112	4.7
	b	1183	5.0
	c	1199	5.0
5.5	a	1003	6
	b	>937	>5.2
	c	>905	>4.7
	a		
	b		
	c		

MARSHALL TOUGHNESS PARAMETER

Mix Design Texaco AC10

AGGREGATE: CRUSHED LIMESTONE

Sample #		Stability	Flow
3.5	a	2497	9.5
	b	2387	9.1
	c	2300	9.1
4.0	a	2713	10
	b	2793	9.5
	c	2747	9.7
4.5	a	2666	11.5
	b	2565	11.3
	c	2594	12.0
5.0	a	2261	12.5
	b	2200	12.7
	c	2588	11.0
5.5	a	1961	13.8
	b	2041	14.2
	c	2109	14.8
	a		
	b		
	c		

LIZ METTING

Date 10/22/86

DATA REDUCTION FORM

*****APPROXIMATION*****

Mix Design TEXACO A C 20

AGGREGATE: RIVER GRAVEL

Sample #	Stability	Flow
4.0 a	1810	5.5
b	1870	6
c	1940	6
4.0 a	1608	5
b	1632	5.5
c	1618	5
4.5 a	1615	7.5
b	1715	6.8
c	1390	7.0
4.5 a	1620	5
b	1600	5.5
c	1780	5.5
5.0 a	1360	6
b	1590	5.5
c	1640	5.8
5.0 a	1400	7.5
b	1400	6.8
c	1390	7.0

MARSHALL TOUGHNESS PARAMETER

Mix Design continued

Sample #	Stability	Flow
5.5 a	1220	8.5
b	1220	7.2
c	1275	7.5
5.5 a	1380	7.5
b	1380	7.5
c	1460	8.0
a		
b		
c		
a		
b		
c		
a		
b		
c		
a		
b		
c		

LIZ METTING

Date 10/22/86

DATA REDUCTION FORM

APPROXIMATION

Mix Design TEXACO AC 10

AGGREGATE : RIVER GRAVEL

Sample #		Stability	Flow
4.0	a	1200	6.0
	b	1190	5.5
	c	1262	5.5
4.5	a	1175	5.7
	b	1253	6.5
	c	1292	6.5
5.0	a	1300	7.5
	b	1235	7.5
	c	1350	7.5
5.5	a	1175	10.5
	b	1105	10
	c	1300	11
6.0	a	1120	10.5
	b	1130	11
	c	1100	10
	a		
	b		
	c		

MARSHALL TOUGHNESS PARAMETER

Mix Design TEXACO AC5

AGGREGATE: RIVER GRAVEL

Sample #		Stability	Flow
4.5	a	850	5.2
	b	985	8.0
	c	925	8.0
5.0	a	985	11
	b	980	9
	c	1020	10
5.5	a	1000	8.5
	b	1020	9.0
	c	1015	8.5
6.0	a	850	5.2
	b	810	9.5
	c	820	10
	a		
	b		
	c		
	a		
	b		
	c		

LIZ METTING

Date 10/22/86

DATA REDUCTION FORM

*****APPROXIMATION*****

Mix Design TEXACO AC5+Latex

AGGREGATE: RIVER GRAVEL

Sample #		Stability	Flow
4.5	a	1017	5.5
	b	1037	5.0
	c	1165	5.2
4.5	a	1150	4.7
	b	1135	5
	c	1120	5.5
5.0	a	1200	5.5
	b	1145	5.0
	c	1200	6.0
5.5	a	1110	7.0
	b	1200	6.5
	c	1223	7.0
6.0	a	900	8.7
	b	875	9.6
	c	940	9.2
	a		
	b		
	c		

MARSHALL TOUGHNESS PARAMETER

Mix Design TEXACO AC10 + CARBON BLACK

AGGREGATE: RIVER GRAVEL

Sample #		Stability	Flow
3.5	a	1367	5.5
	b	1386	5.0
	c	1469	4.8
4.0	a	1460	6
	b	1414	6
	c	1395	6
4.5	a	1382	5.5
	b	1416	5.0
	c	1392	5.5
5.0	a	1229	5.3
	b	1219	6
	c	1459	5.8
		F	
5.5	a	1465	6.5
	b	1505	5.8
	c	1525	6.5
	a		
	b		
	c		

LIZ METTING

Date 10/22/86

DATA REDUCTION FORM

APPROXIMATION

MARSHALL TOUGHNESS PARAMETER

Mix Design KRATON
AGGREGATE: RIVER GRAVEL

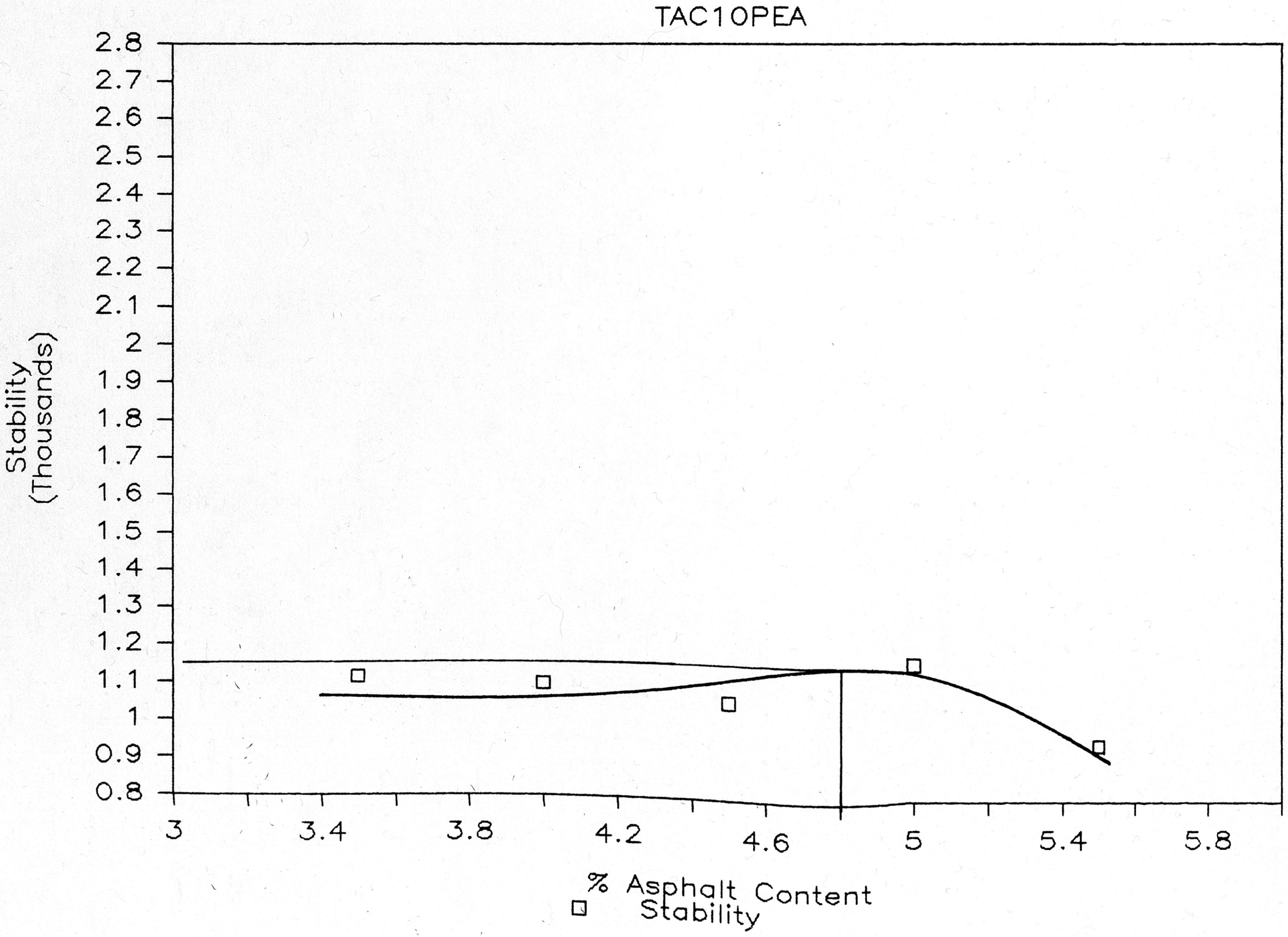
Sample #	Stability	Flow
3.5 a	1325	4.5
b	1426	5.0
c	1411	4.5
4.0 a	1635	5.0
b	1585	5.0
c	1670	6.0
4.5 a	—	—
b	1478	5
c	1440	6
5.0 a	1325	7
b	1410	6
c	1485	6
5.5 a	1315	11.5
b	1338	10
c	1335	10
a		
b		
c		

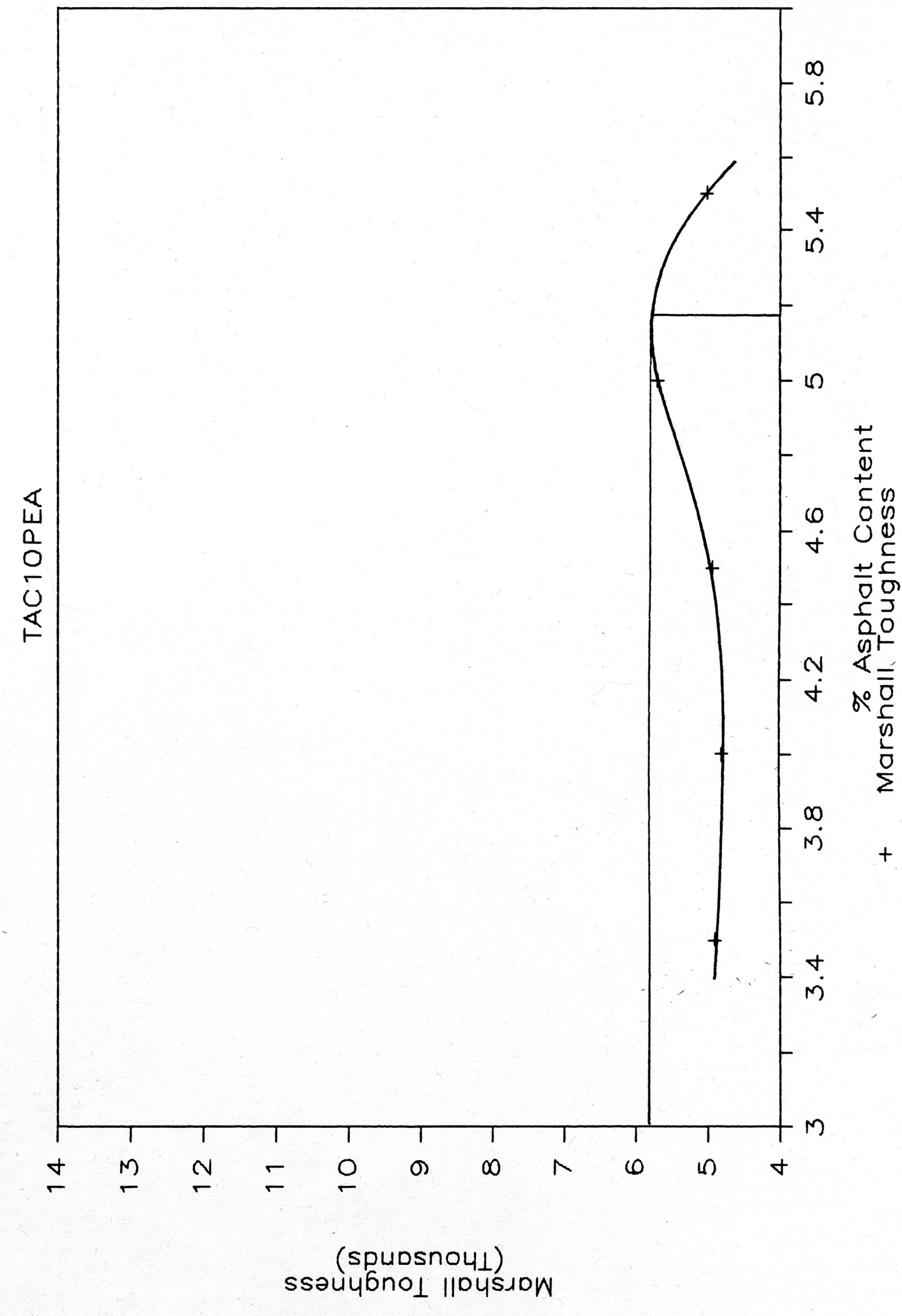
Mix Design NOVOPHALT
AGGREGATE: RIVER GRAVEL

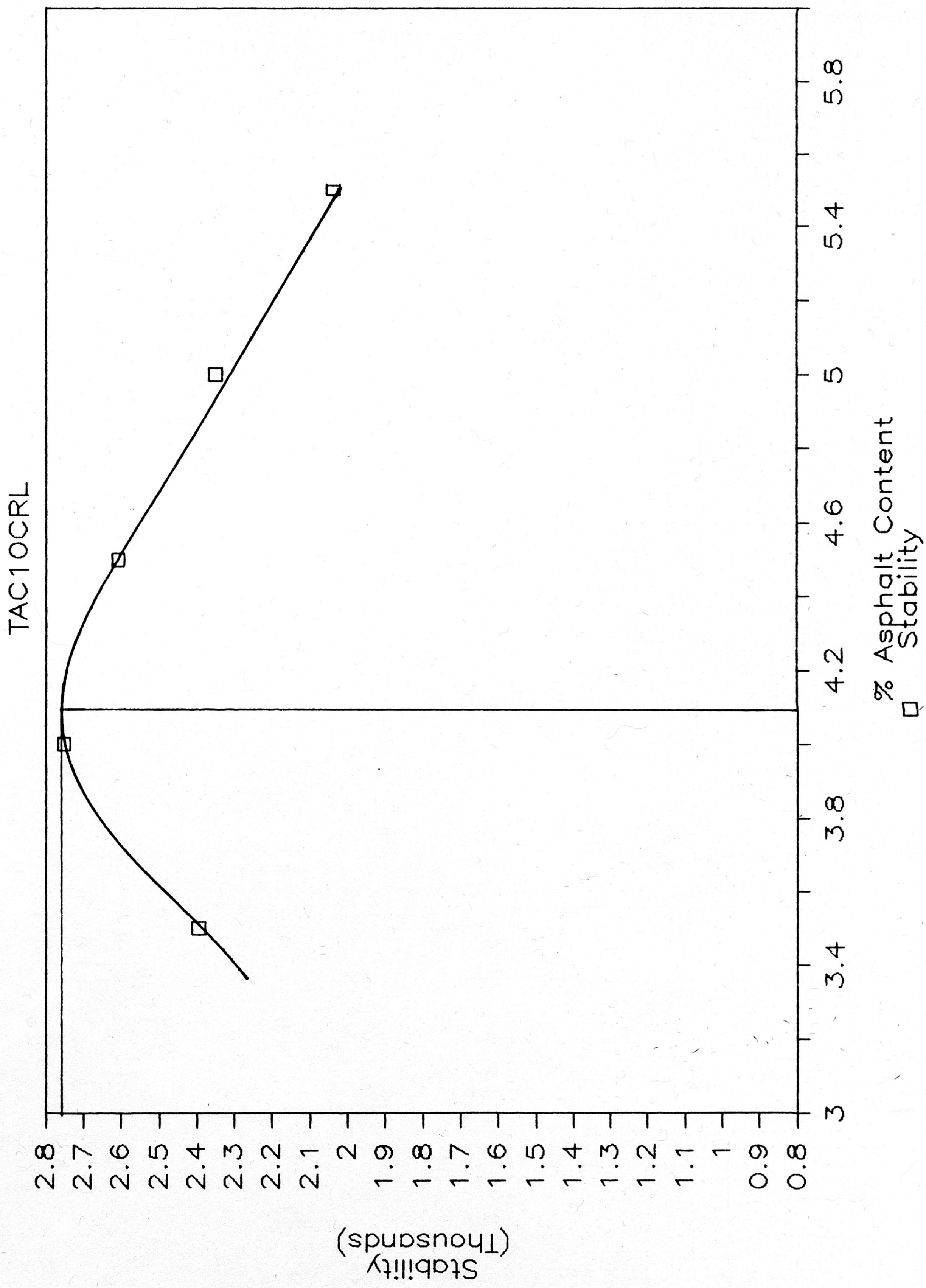
Sample #	Stability	Flow
4.0 a	1344	5
b	1344	5
c	1368	5
4.5 a	1460	6.2
b	1325	5.7
c	1450	5.6
5.0 a	1290	6
b	1380	6.3
c	1370	6.2
5.5 a	1270	8.5
b	1340	8
c	1325	8
a		
b		
c		
a		
b		
c		

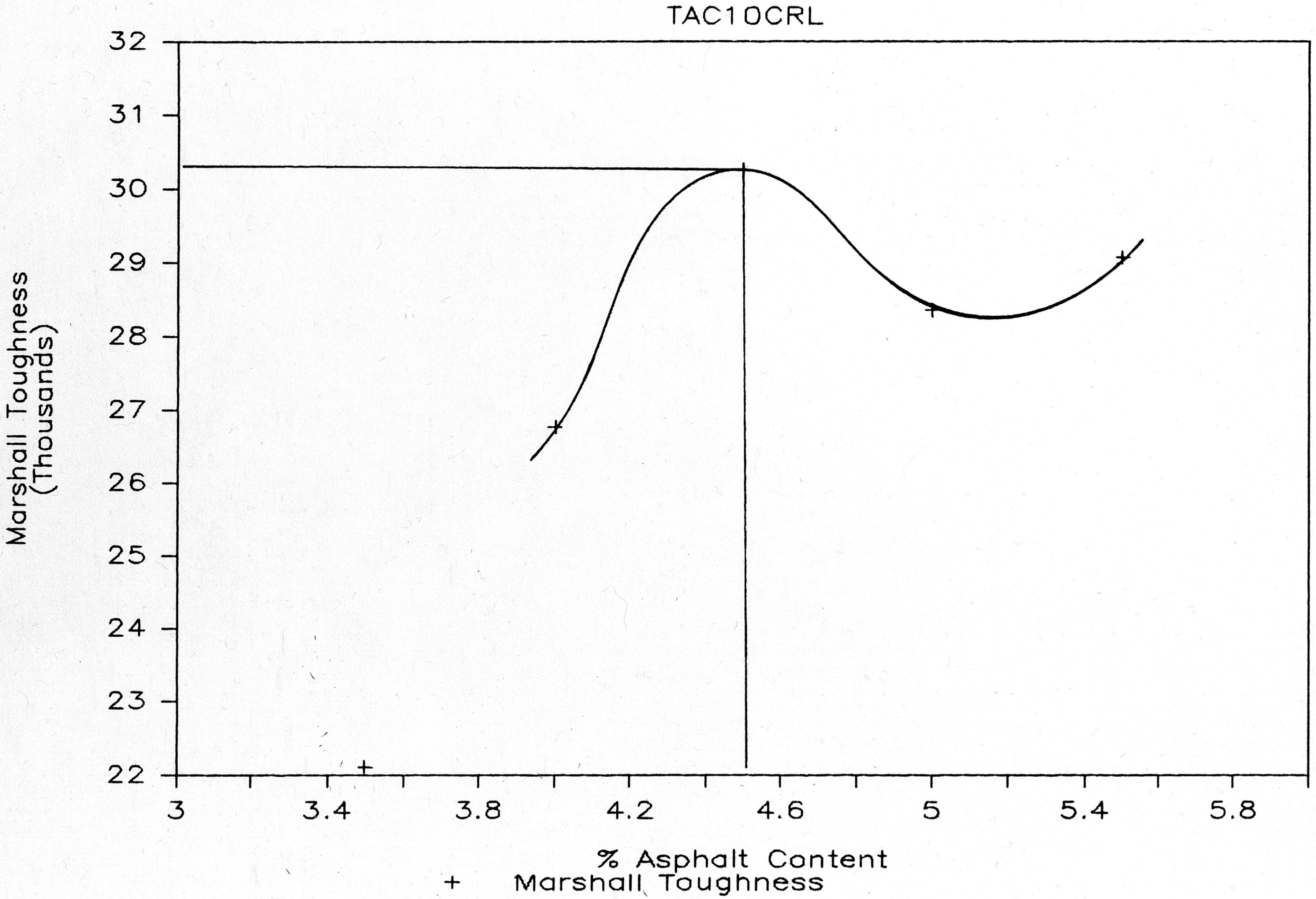
Mix Design	Asphalt %	Average		Marshall Toughness Approximation	Sample A		Sample B		Sample C		Sample D		Sample E		Sample F	
		Stability	Flow		Stability	Flow	Stability	Flow	Stability	Flow	Stability	Flow	Stability	Flow	Stability	Flow
TAC10PEA	3.5	1115	4.4	4904.5	1050	4.5	1150	4.5	1144	4.2						
TAC10PEA	4.0	1099	4.4	4799.0	1014	4.5	1139	4.1	1144	4.5						
TAC10PEA	4.5	1059	4.7	4943.6	1050	5.0	1082	4.5	1046	4.5						
TAC10PEA	5.0	1165	4.9	5706.9	1112	4.7	1183	5.0	1199	5.0						
TAC10PEA	5.5	948	5.3	5026.2	1003	6.0	937	5.2	905	4.7						
TAC10CRL	3.5	2395	9.2	22110.8	2497	9.5	2387	9.1	2300	9.1						
TAC10CRL	4.0	2751	9.7	26776.4	2713	10.0	2793	9.5	2747	9.7						
TAC10CRL	4.5	2608	11.6	30256.7	2666	11.5	2565	11.3	2594	12.0						
TAC10CRL	5.0	2350	12.1	28352.6	2261	12.5	2200	12.7	2588	11.0						
TAC10CRL	5.5	2037	14.3	29061.2	1961	13.8	2041	14.2	2109	14.8						
TAC20RG	4.0	1746	5.5	9604.8	1810	5.5	1870	6.0	1940	6.0	1608	5.0	1632	5.5	1618	5.0
TAC20RG	4.5	1677	5.5	9221.7	1615	6.0	1715	5.5	1730	5.5	1620	5.0	1600	5.5	1780	5.5
TAC20RG	5.0	1497	6.4	9628.6	1560	6.0	1590	5.5	1640	5.8	1400	7.5	1400	6.8	1390	7.0
TAC20RG	5.5	1323	7.7	10183.3	1220	8.5	1220	7.2	1275	7.5	1380	7.5	1380	7.5	1460	8.0
TAC10RG	4.0	1217	5.7	6898.2	1200	6.0	1190	5.5	1262	5.5						
TAC10RG	4.5	1240	6.2	7729.3	1175	5.7	1253	6.5	1292	6.5						
TAC10RG	5.0	1295	7.5	9712.5	1300	7.5	1235	7.5	1350	7.5						
TAC10RG	5.5	1193	10.5	12530.0	1175	10.5	1105	10.0	1300	11.0						
TAC10RG	6.0	1117	10.5	11725.0	1120	10.5	1130	11.0	1100	10.0						
TAC5RG	4.5	920	7.1	6501.3	850	5.2	985	8.0	925	8.0						
TAC5RG	5.0	995	10.0	9950.0	985	11.0	980	9.0	1020	10.0						
TAC5RG	5.5	1012	8.7	8767.8	1000	8.5	1020	9.0	1015	8.5						
TAC5RG	6.0	827	8.2	6806.2	850	5.2	810	9.5	820	10.0						
TAC5RG+LATEX	4.5	1104	5.7	6237.6	1017	5.5	1037	5.0	1165	5.2	1150	7.7	1135	5.0	1120	5.5
TAC5RG+LATEX	5.0	1182	5.5	6499.2	1200	5.5	1145	5.0	1200	6.0						
TAC5RG+LATEX	5.5	1178	6.8	8051.9	1110	7.0	1200	6.5	1225	7.0						
TAC5RG+LATEX	6.0	905	9.2	8295.8	900	8.7	875	9.6	940	9.2						
TAC10RG+CARB	3.5	1407	5.1	7177.4	1367	5.5	1386	5.0	1469	4.8						
TAC10RG+CARB	4.0	1423	6.0	8538.0	1460	6.0	1414	6.0	1395	6.0						
TAC10RG+CARB	4.5	1397	5.3	7448.9	1382	5.5	1416	5.0	1392	5.5						
TAC10RG+CARB	5.0	1302	5.8	7510.1	1229	5.5	1219	6.0	1459	5.8						
TAC10RG+CARB	5.5	1498	6.3	9389.6	1465	6.5	1505	5.8	1525	6.5						
KRATON RG	3.5	1387	4.7	6474.2	1325	4.5	1426	5.0	1411	4.5						
KRATON RG	4.0	1630	5.3	8693.3	1635	5.0	1585	5.0	1670	6.0						
KRATON RG	4.5	1459	5.5	8024.5			1478	5.0	1440	6.0						
KRATON RG	5.0	1407	6.3	8908.9	1325	7.0	1410	6.0	1485	6.0						
KRATON RG	5.5	1329	10.5	13958.0	1315	11.5	1338	10.0	1335	10.0						
NOVOPHALT RG	4.0	1352	5.0	6760.0	1344	5.0	1344	5.0	1368	5.0						
NOVOPHALT RG	4.5	1478	5.8	8623.6	1460	6.2	1525	5.7	1450	5.6						
NOVOPHALT RG	5.0	1347	6.2	8304.4	1290	6.0	1380	6.3	1370	6.2						
NOVOPHALT RG	5.5	1312	8.2	10711.9	1270	8.5	1340	8.0	1325	8.0						

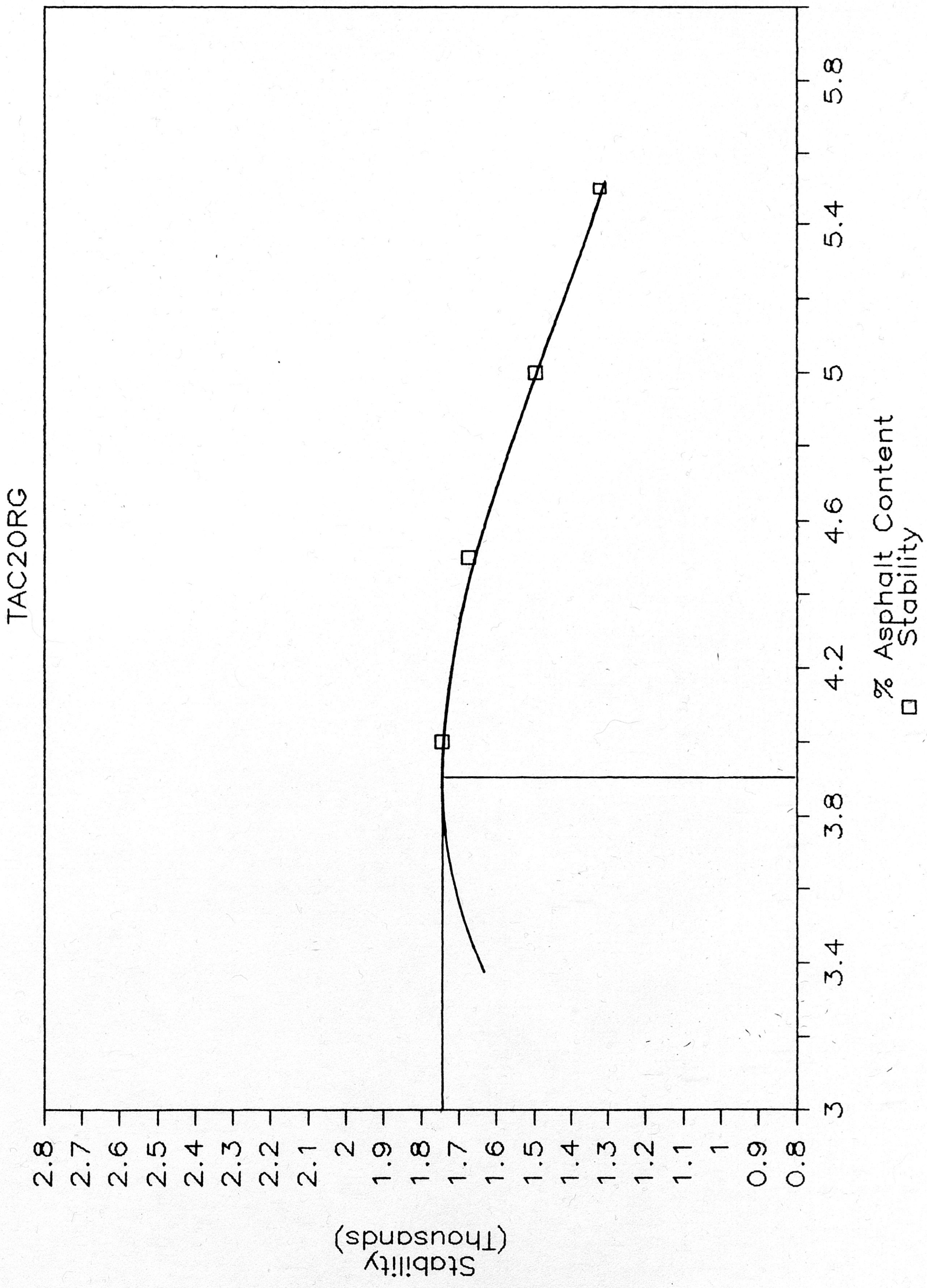
Calculation of Marshall Toughness Parameter

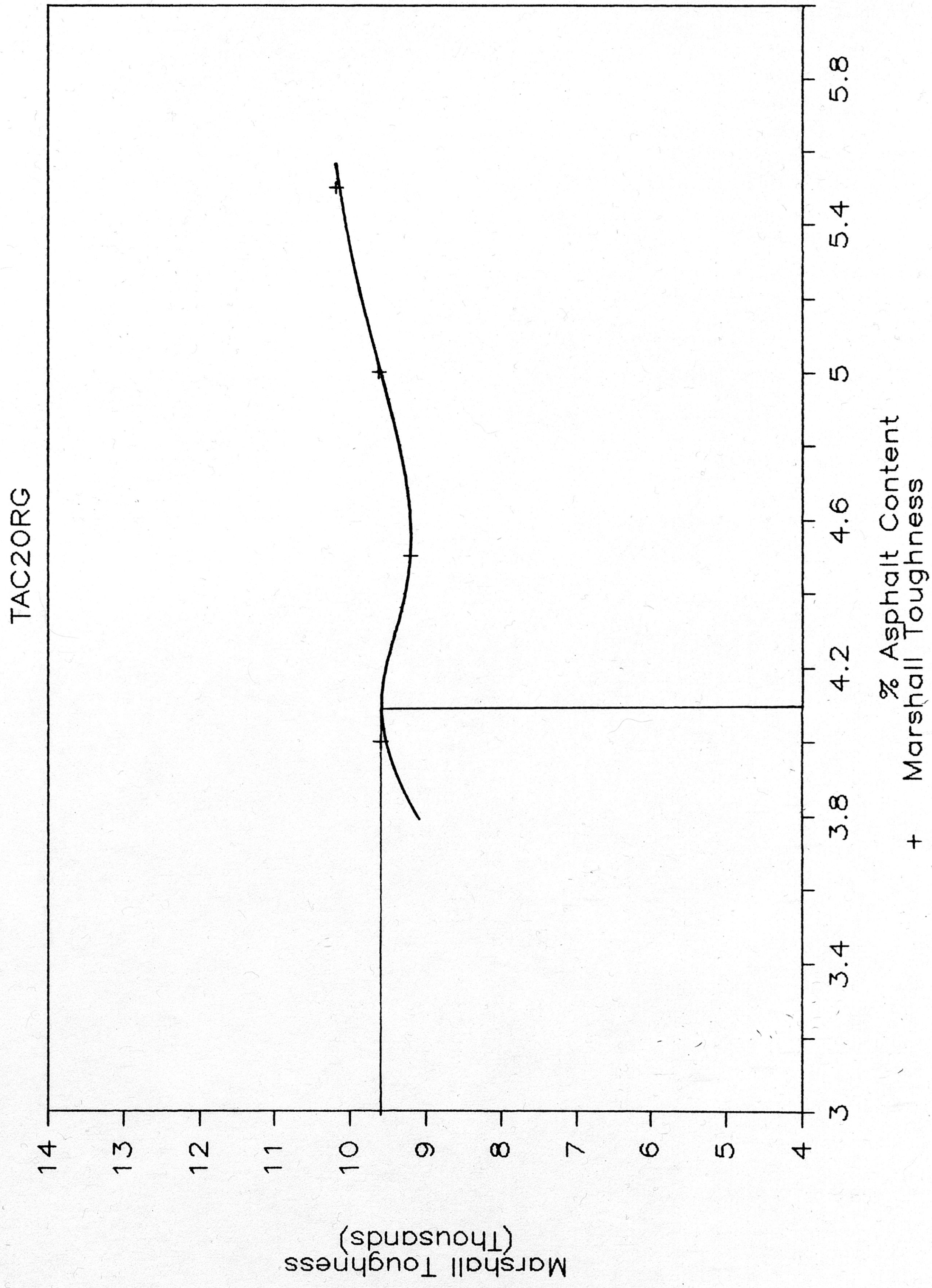

TAC10PEA
Stability
(Thousands)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
□ Stability

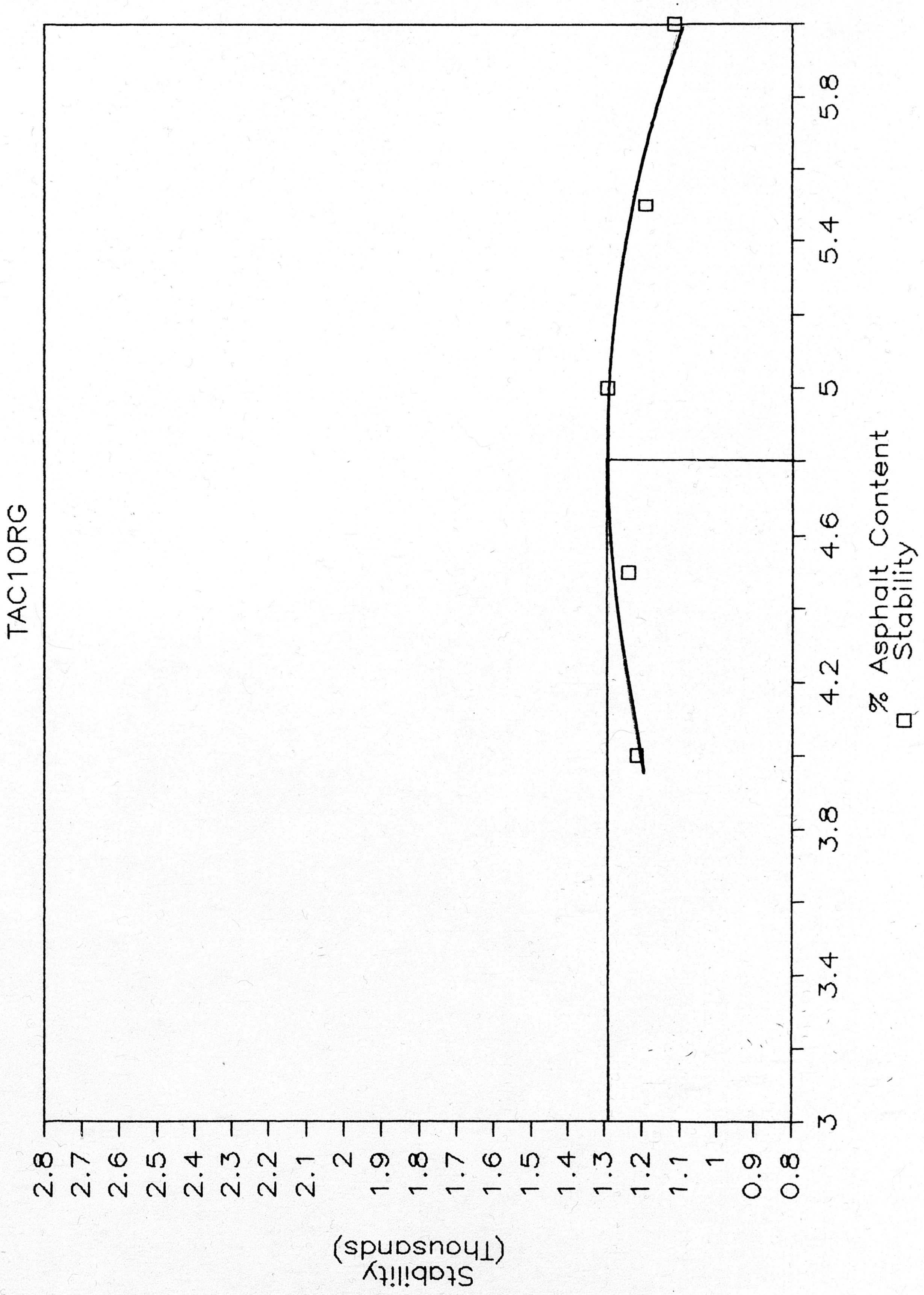

TAC1OPEA
Marshall Toughness
(Thousands)
14
13
12
11
10
9
8
7
6
5
4
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness

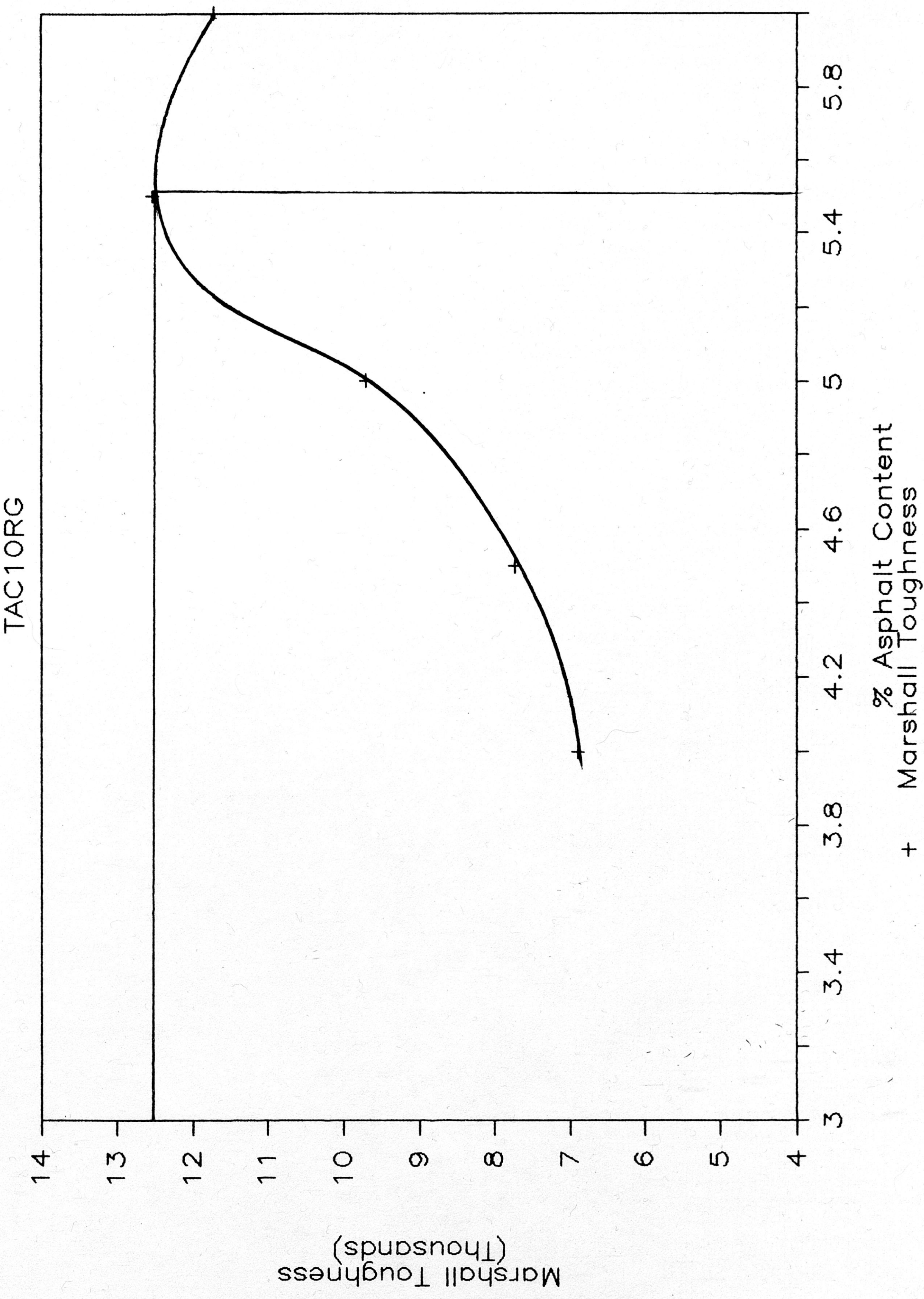

TAC10CRL
Stability
(Thousands)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
□ Stability

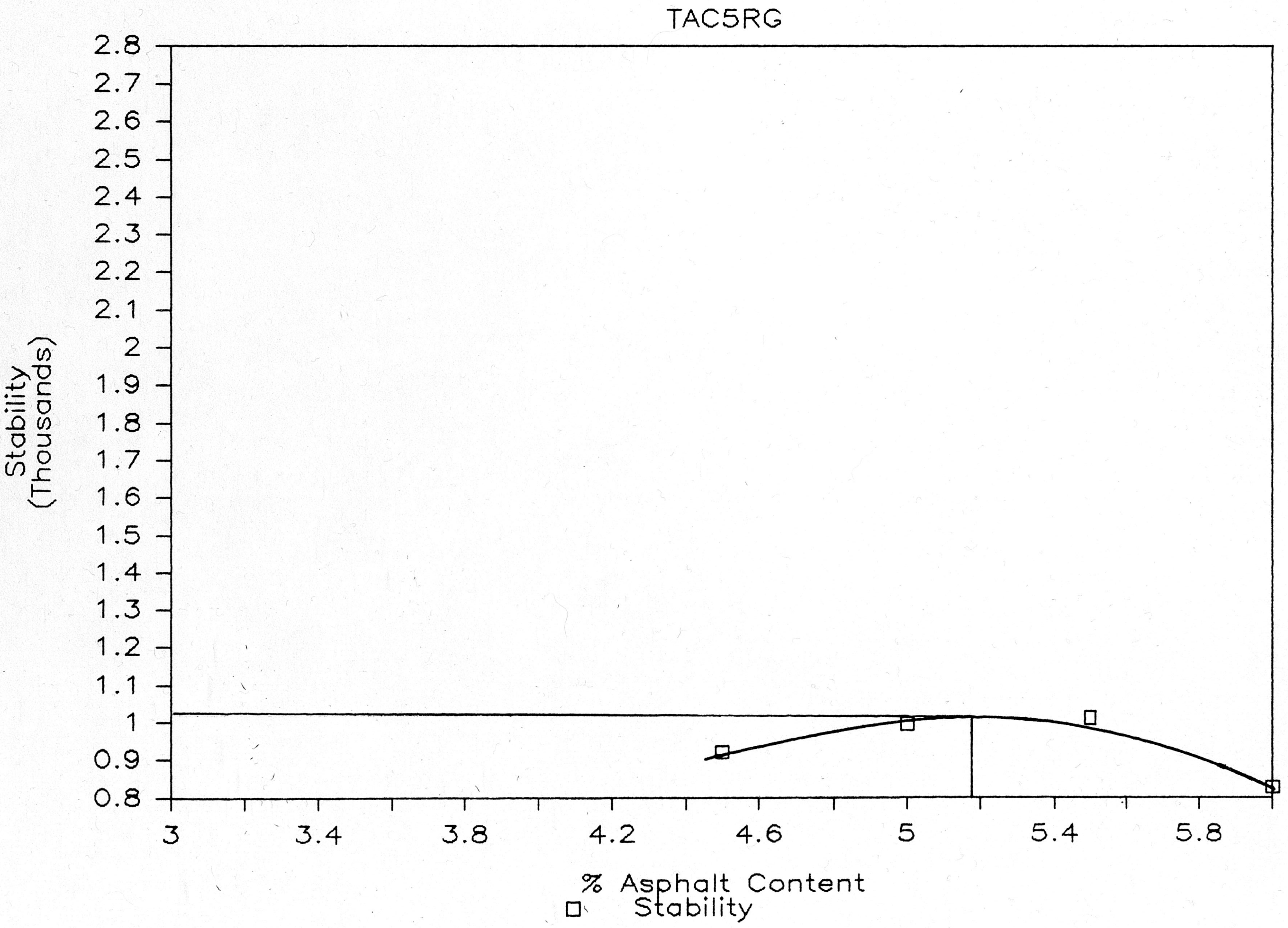

TAC10CRL
Marshall Toughness (Thousands)
32
31
30
29
28
27
26
25
24
23
22
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness

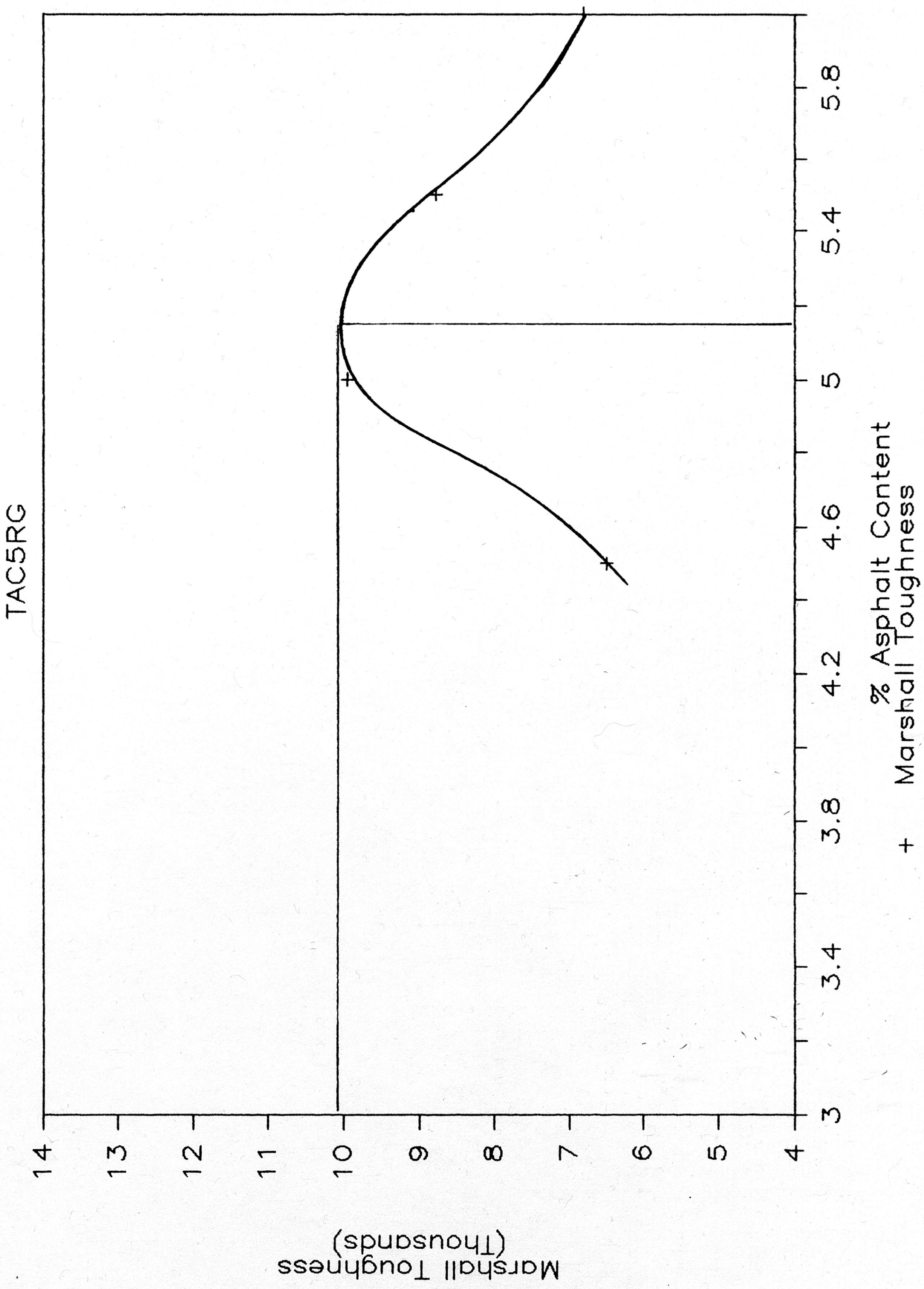

TAC20RG
Stability (Thousands)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
□ Stability

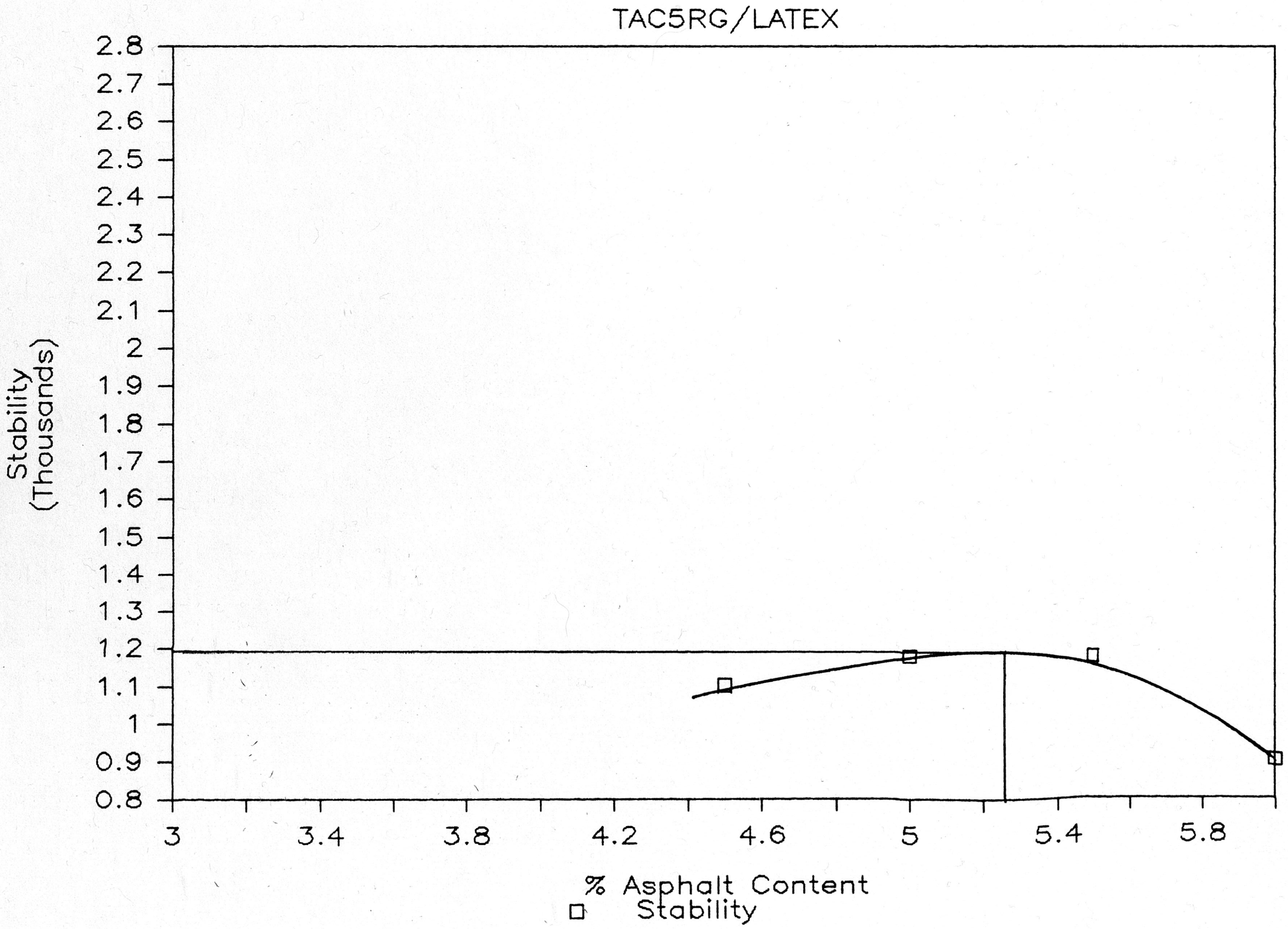

TAC20RG
Marshall Toughness (Thousands)
14
13
12
11
10
9
8
7
6
5
4
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness

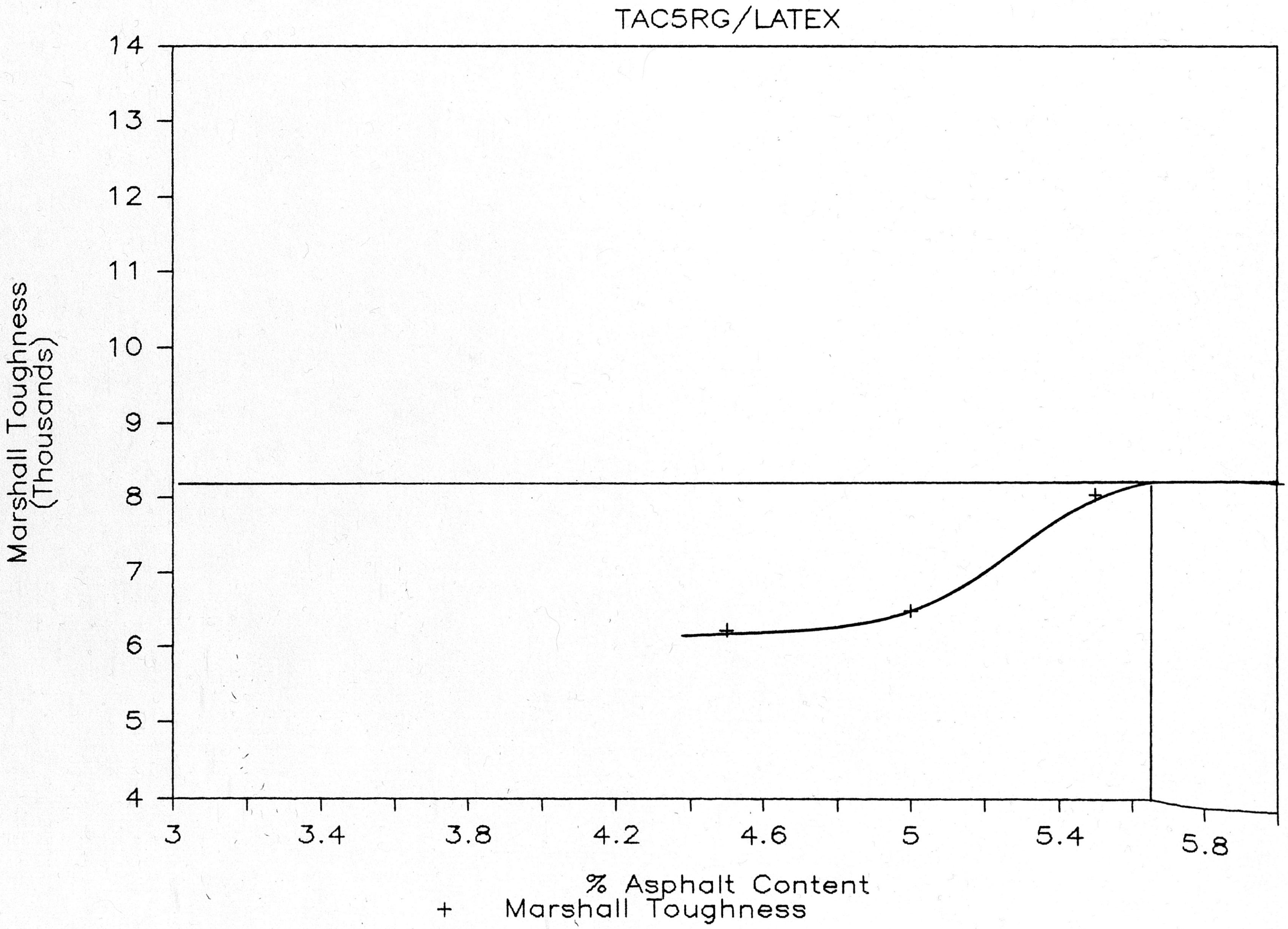

TAC10RG
Stability
(Thousands)
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
Stability

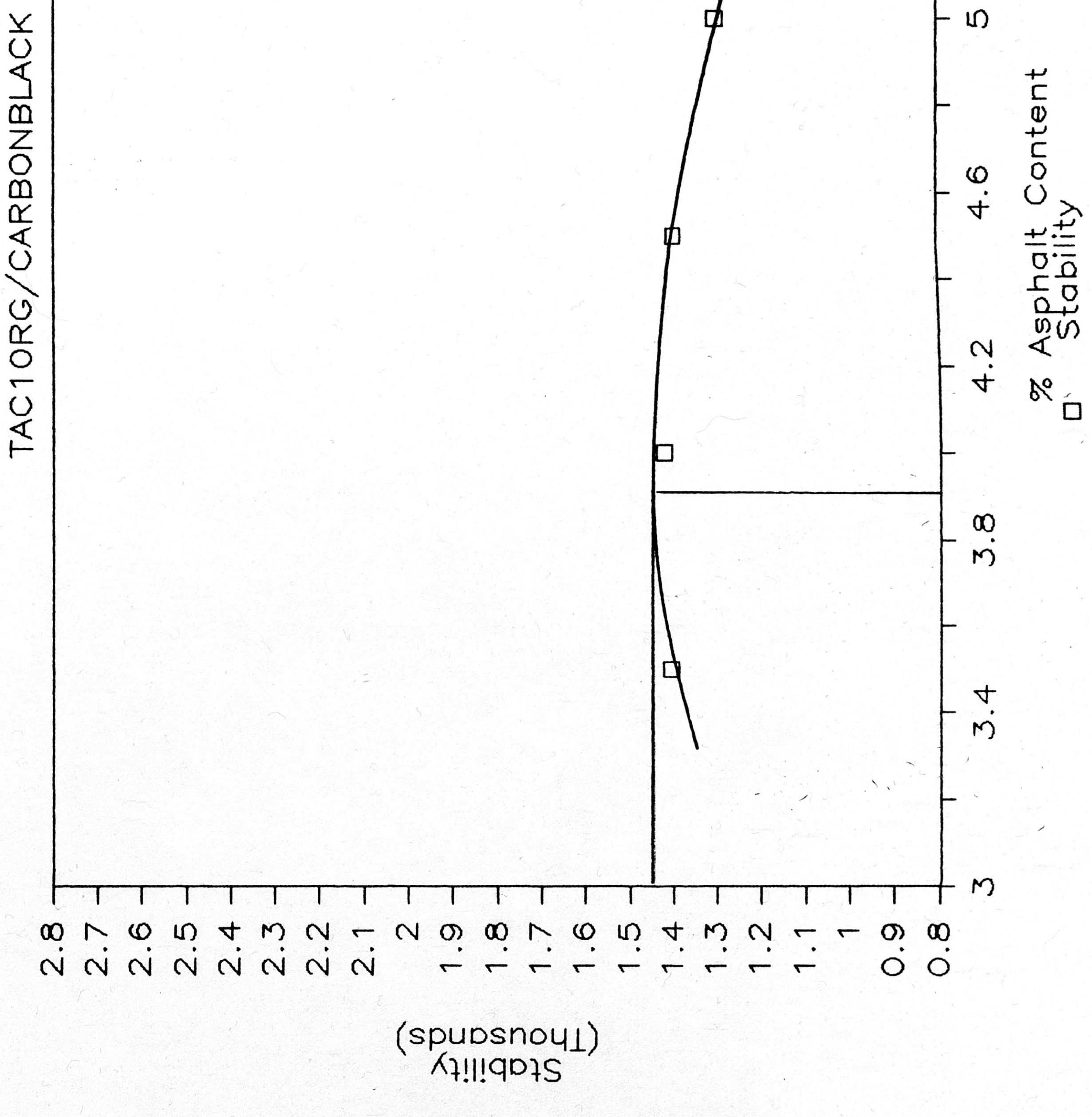

TAC10RG
Marshall Toughness (Thousands)
14
13
12
11
10
9
8
7
6
5
4
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness

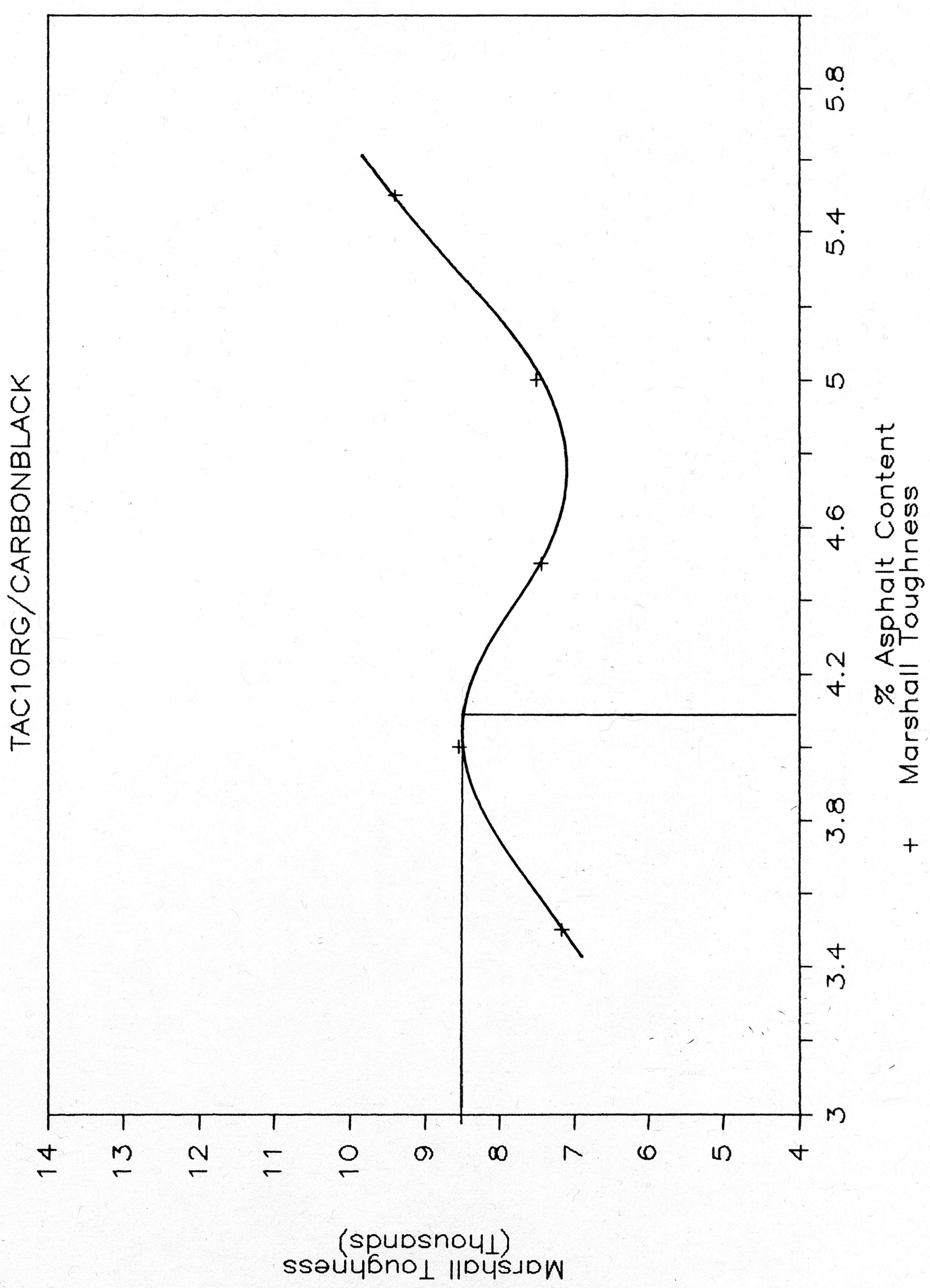

TAC5RG
Stability
(Thousands)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
□ Stability

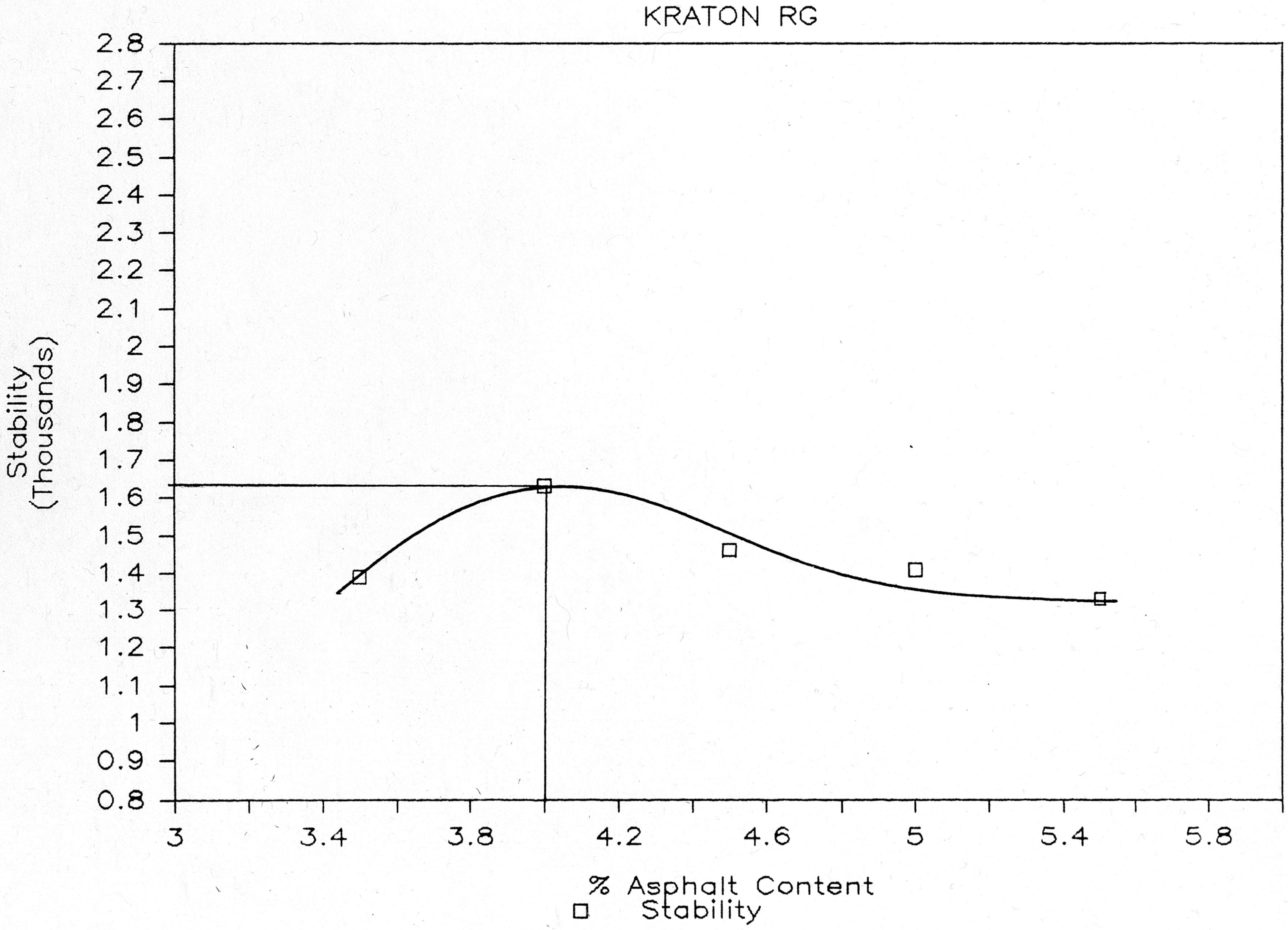

TAC5RG
Marshall Toughness
(Thousands)
14
13
12
11
10
9
8
7
6
5
4
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness

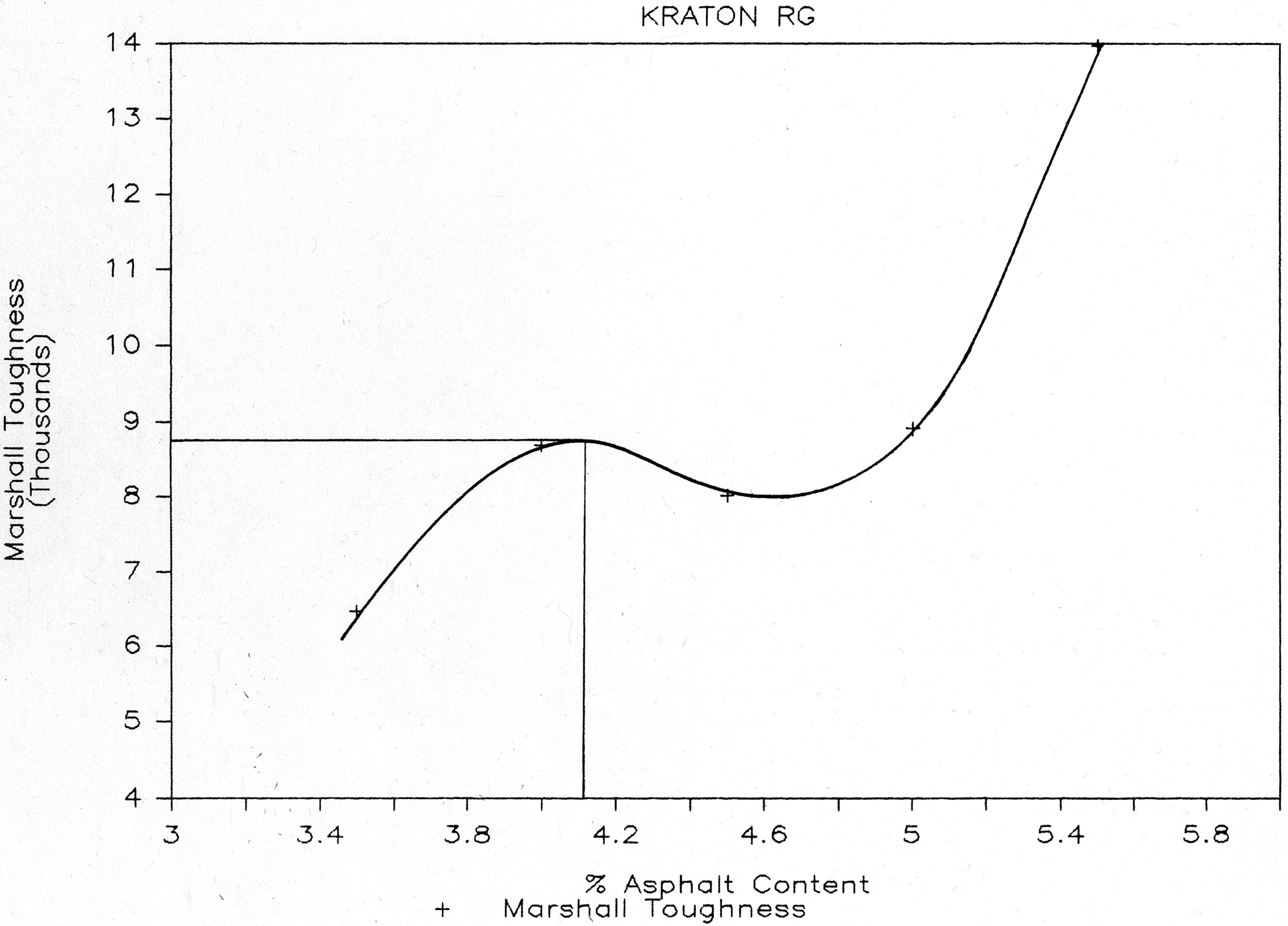

TAC5RG/LATEX
Stability
(Thousands)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
□ Stability


TAC5RG/LATEX
Marshall Toughness
(Thousands)
14
13
12
11
10
9
8
7
6
5
4
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness


TAC10RG/CARBONBLACK
Stability
(Thousands)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
□ Stability

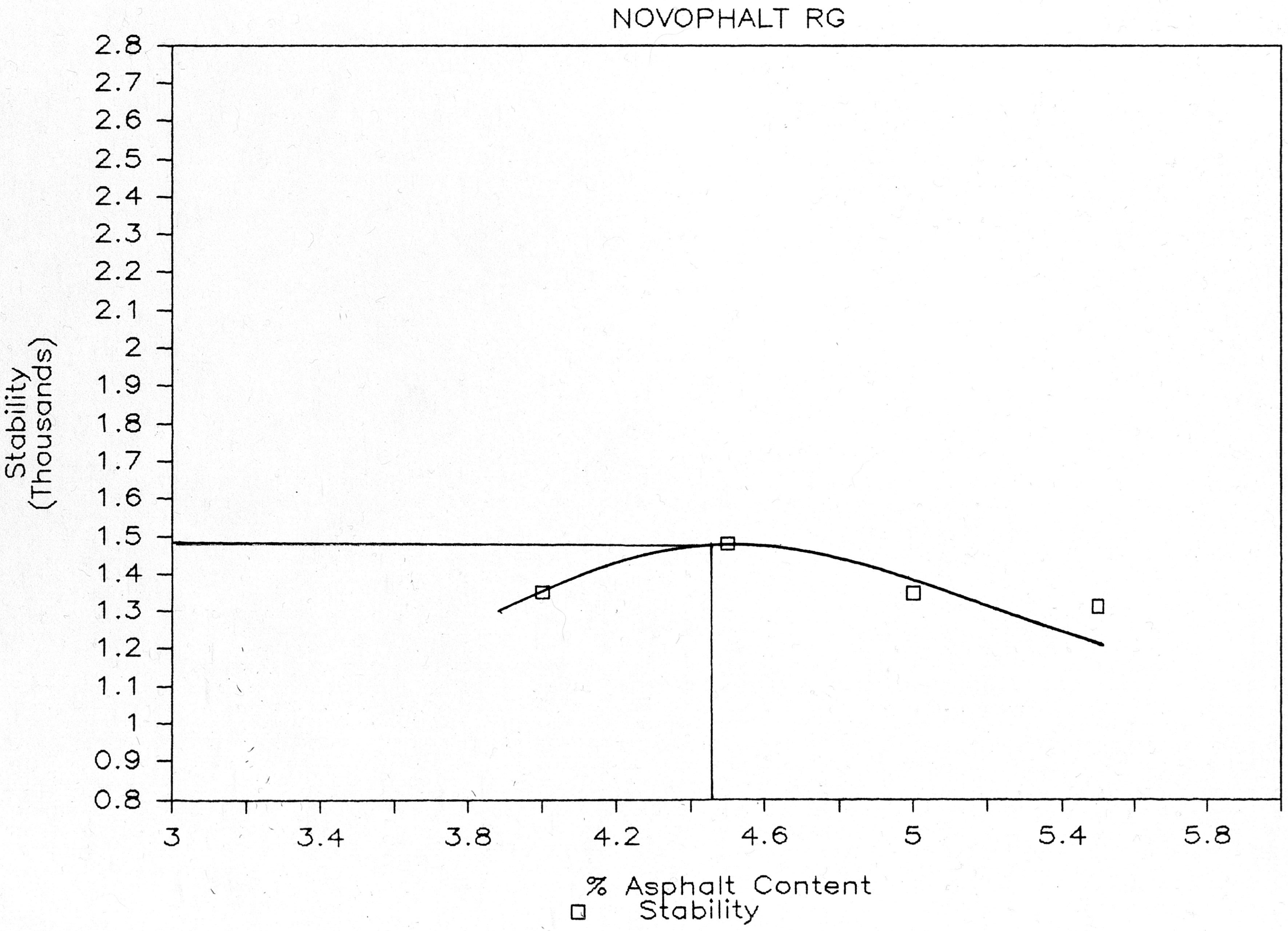

TAC10RG/CARBONBLACK
Marshall Toughness
(Thousands)
14
13
12
11
10
9
8
7
6
5
4
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness

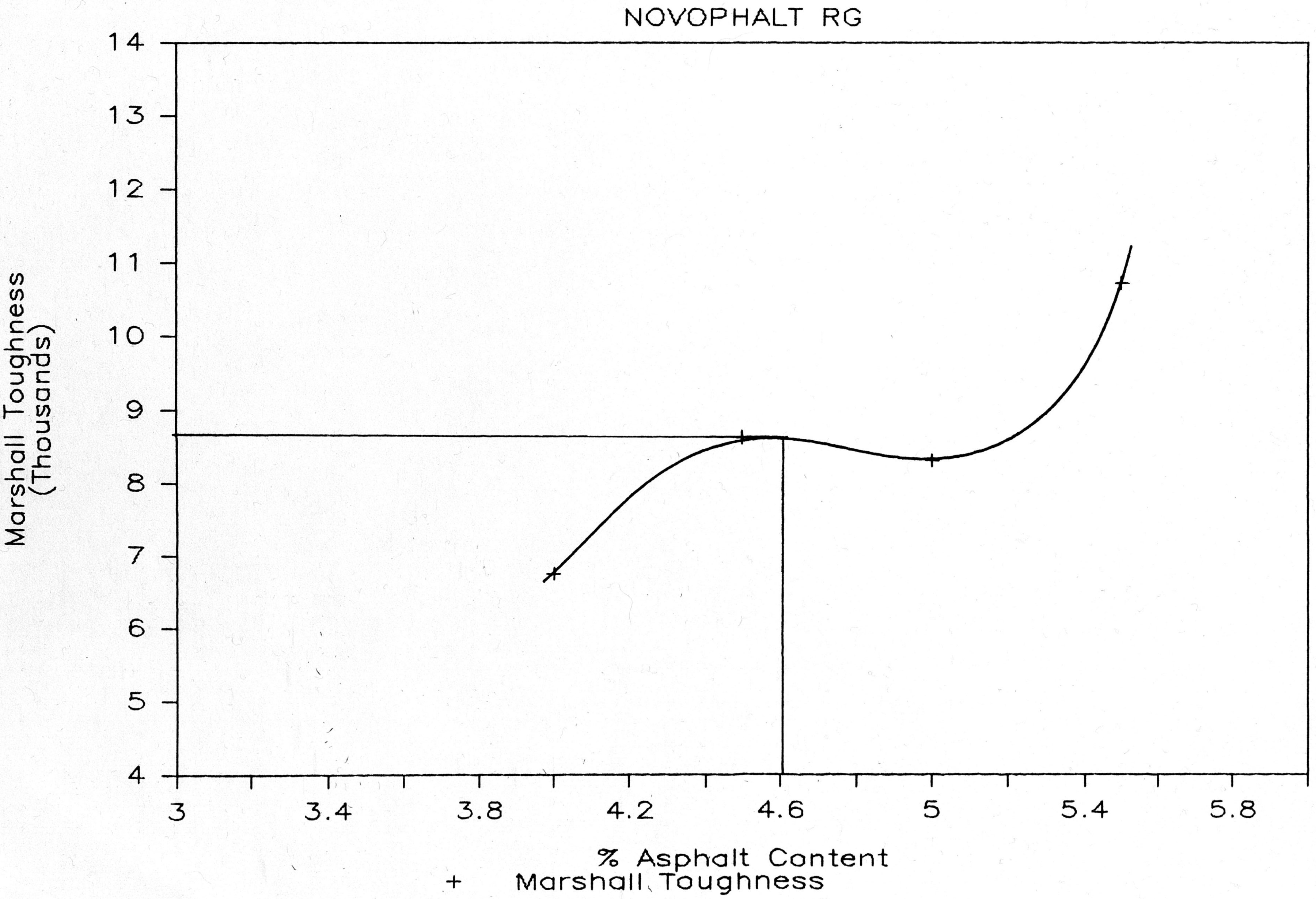

KRATON RG
Stability
(Thousands)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
□ Stability



KRATON RG

Marshall Toughness
(Thousands)
14
13
12
11
10
9
8
7
6
5
4
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness


NOVOPHALT RG
Stability
(Thousands)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
□ Stability


NOVOPHALT RG
Marshall Toughness
(Thousands)
14
13
12
11
10
9
8
7
6
5
4
3
3.4
3.8
4.2
4.6
5
5.4
5.8
% Asphalt Content
+ Marshall Toughness