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JANUARY 1973

FINAL REPORT
ISU – ERI – AMES – 72251

EVALUATION OF GAP-GRADED ASPHALT CONCRETE MIXTURES
PART I: MECHANICAL PROPERTIES

Iowa Highway Research Board
Project HR-157

ERI Project 900-S

Prepared in cooperation with the
Iowa State Highway Commission
and the U. S. Department of Transportation
Federal Highway Administration

ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY
AMES, IOWA 50010 USA

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16. Abstract

This report presents the results of a comparative laboratory study between well- and gap-graded aggregates used in asphalt concrete paving mixtures. A total of 424 batches of asphalt concrete mixtures and 3,960 Marshall and Hveem specimens were examined.

There is strong evidence from this investigation that, with proper combinations of aggregates and asphalts, both continuous- and gap-graded aggregates can produce mixtures of high density and of qualities meeting current design criteria. There is also reason to believe that the unqualified acceptance of some supposedly desirable, constant, mathematical relationship between adjacent particle sizes of the form such as Fuller's curve $p = 100(d/D)^n$ is not justified. It is recommended that the aggregate grading limits be relaxed or eliminated and that the acceptance or rejection of an aggregate for use in asphalt pavement be based on individual mixture evaluation.

Furthermore, because of the potential attractiveness of gap-graded asphalt concrete in cost, quality, and skid and wear resistance, selected gap-graded mixtures are recommended for further tests both in the laboratory and in the field, especially in regard to ease of compaction and skid and wear resistance.

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EXECUTIVE SUMMARY

Because of the increasing demand for high quality, more durable, high skid- and wear-resistant paving mixtures for modern traffic, and because of the increasing costs for producing maximum density or well-graded aggregates in many parts of the country (especially near urban areas), the potential advantages of using gap-graded aggregates in both portland cement and asphalt concretes are attracting attention throughout the world.

This report presents the results of a comparative laboratory study between well-graded and gap-graded aggregates used in asphalt concrete paving mixtures. There was a total of 424 batches of asphalt concrete mixtures and 3,960 Marshall and Hveem specimens.

There is strong evidence from this investigation that, with proper combinations of aggregates and asphalts, both continuous and gap-graded aggregates can produce mixtures of high density and of qualities meeting current design criteria. There is also reason to believe that the unqualified acceptance of some supposedly desirable, constant, mathematical relationship between adjacent particle sizes of the form such as Fuller's curve $p = 100 \left(\frac{d}{D}\right)^n$ is not justified. It is recommended that the aggregate grading limits be relaxed or eliminated and that the acceptance or rejection of an aggregate to be used in asphalt pavement be based on individual mixture evaluation.

Furthermore, because of the potential attractiveness of gap-graded asphalt concrete in cost, quality, skid and wear resistance, and construction, selected gap-graded mixtures are recommended for further tests both in the laboratory and in the field, especially in regard to ease of compaction and skid and wear resistance.

localities; (b) they may allow more asphalt to be used in the mixture, thus giving thicker asphalt films and more durable paving mixture; (c) they may have better flexibility, higher strain value at failure due to use of a higher low-penetration asphalt content; (d) they may be more skid resistant; (e) they may be more wear resistant; (f) they may tolerate more asphalt content variations; and (g) they may be easier to compact.

On the other hand, the continuous grading has been criticized for at least three disadvantages that deserve reexamination. Some countries, such as Japan, that traditionally specify continuous grading for their high-type asphalt mixtures, have already been studying the feasibility of gap-grading mixtures[5]. The major disadvantages of well-graded mixtures are: (a) they are more expensive to produce, especially for some state where suitable aggregate sources are depleting and where narrow limits are specified; (b) they are more sensitive to asphalt content change, leading to disintegration on the one hand and slipperiness on the other[12]; and (c) they are difficult to handle, and tend to segregate[7].

Much data, especially theoretical, can be found on the packing of aggregate particles and maximum density or minimum porosity gradings, including the classic work on concrete proportioning by Fuller and Thompson and the more recent work on dense asphaltic mixtures by Lee[13] and Huang[14]. There is also abundant published information on gap-graded concretes as compared to the corresponding continuously graded concretes[15-17]. However, reported data on gap-graded asphalt concrete mixtures are few and scattered. When the subject was introduced and discussed, no consensus could be reached[18].

Preliminary study[19] conducted in the Bituminous Research Laboratory, Iowa State University, involving three Fuller's gradings, eight gap gradings, two crushed limestone, and one asphalt cement indicated that:

1. Mixtures can be designed by either the Marshall or Hveem method for all aggregates, both continuous graded and gap graded, to meet recommended design criteria for all relevant properties.
2. While in most cases the Fuller grading yielded mixtures of highest density, the gap-graded mixtures often resulted in better stability or cohesion.
3. With almost no exception, gap-graded mixtures had higher optimum asphalt content that equivalent Fuller-graded mixtures.
4. At least for the aggregates studied, rigid requirements for the aggregate to meet Fuller's grading or stringent gradation tolerance control, especially involving additional processing and transportation cost, may not be justified.

The purpose of HR-157 is to make a more exhaustive and systematic study of gap-graded asphalt concrete mixtures in comparison with Fuller's curve gradings and Iowa Type A gradings, including more aggregate types and sources, more asphalt grades, wider asphalt content variation, a study based on more relevant mixture properties.

I. INTRODUCTION

Engineers in the field of bituminous paving generally agree that aggregate gradation in a paving mixture is one of the factors that must be carefully considered in a mixture design. It affects, directly or indirectly, the density, stability, durability, skid-resistance and economy of the finished pavement. Virtually all high-type asphalt concrete used in the United States now employs a densely graded aggregate. However, there are differences of opinion in various localities about what constitutes the "ideal" gradation for densely graded aggregate and the rationale behind the use of densely graded aggregates.

An examination of the gradation requirements of specifications used by various state highway departments and other agencies in the U.S., Canada and some European countries reveals that in nearly all cases (with a few exceptions, such as British Standard 594) these requirements approximate Fuller's maximum density curves[1,2]. It can also be observed that: (a) specifications on aggregate gradation differ greatly, and tolerance of gradation limits vary widely; (b) under certain sets of conditions, a number of gradations can produce satisfactory paving mixtures, and (c) present knowledge on aggregate gradation, when coupled with economic considerations, may not justify the application of narrow gradation limits.

Of special significance are reported experiences[3] where successful paving mixtures were associated with the most unconventional and irregular grading curves, and failures identified with gradings complied closely with the ideal maximum density curves such as presented by Fuller.

II. PURPOSE AND SCOPE

The immediate objective of this research was to conduct a systematic comparative study of gap-graded versus continuous-graded asphalt concrete mixtures involving three aggregate types, three maximum sizes, two asphalt grades, and a wide range of asphalt contents. Tests were to be conducted to evaluate the effects of gap grading on stability, cohesion, maximum density, voids, water resistance properties, and optimum asphalt contents.

As a secondary objective, the effects of a number of mixture design variables on mixture stability was to be evaluated by the application of fractional factorial experiment design and analysis[20-22].

The ultimate objective is to select gap-graded aggregate mixtures suitable for field evaluation and eventual incorporation in Iowa specifications.

III. EXPERIMENTAL INFORMATION

A. Materials

Aggregates

Two crushed limestones with varying chemical composition, one natural, one crushed gravel, and one concrete sand were included in this study.

The Ferguson aggregate (L_1) is a dolomite limestone and was used in Series A, B, and C. The Moscow aggre (L_2) is a lithographic limestone and was used in Series D. The crushed and pit-run gravels, taken from Akron pit, Plymouth County, were used in Series A and F respectively. The concrete sand was used in all series for fractions retained No. 30 and retained No. 50 at a 50-50 ratio. The sources and petrographical descriptions of the aggregates are given in Appendix A. The chemical and physical properties of the aggregates are given in Table 1. The particle shape index was determined by Huang's method[23] using standard CBR mold. By this method, a mass of single-sized, highly polished aluminum spheres is taken as zero. The value of particle shape becomes progressively greater as the aggregate particles become more irregular in shape, more angular and more roughly surfaced.

There were no appreciable differences in particle shape among the aggregates studied, as is indicated by the shape index. The major differences between the two crushed limestones were in chemical composition (dolomite content) and in percent wear in L.A. Abrasion test, which reflects the differences in mineral composition; the Ferguson aggregate was softer than the Moscow aggregate.

Table 1. Chemical and physical properties of aggregates.

Property		Aggregates L1 (Ferguson)	L2 (Moscow)	Crushed gravel (G)
Sp. gr.:	bulk ave.	2.521	2.641	2.609
	apparent ave.	2.757	2.714	2.736
Chemical composition				
$CaCO_3$, %		80.39	95.97	—
$MgCO_3$, %		18.90	2.22	—
Insolubles, %		3.06	5.12	—
L. A. abrasion, %				
Grading A & B		39.90	29.90	23.70
Grading C		36.70	28.50	27.50
Shape index[a]		18.20	18.90	19.20
Series		A, B, C	D	A, F

[a]Using standard CBR mold (Ref. 23).

Seventeen aggregate gradings were examined for 3/4-in. maximum size aggregates, including a gradation following Fuller's maximum density curve (A-F), $P = 100(d/D)^{0.45}$ (A-P)[24], a midpoint Iowa Type A grading (A-I)[25] and 14 gap gradings. They were: Four gradings following the BPR curve but with gaps introduced by increasing fines (above the BPR curve): A-4, gaps between 3/8-in. and No. 4 sieve; A-8, gaps between No. 4 and No. 8 sieves; A-30, gaps between No. 8 and No. 30 sieves; and A-100, gaps between No. 30 and No. 100 sieves. Four gradings following the BPR curve with gaps the same as above but introduced by decreasing fines (below the BPR curve): A-4L, A-8L, A-30L and A-100L. Six gradings following the BPR curve but with one-half the amount of gaps as above: A-4H, A-4LH, A-8H, A-8LH, A-30H and A-30LH. These gradings are shown in Table 2 and Fig. 1a and 1b.

Table 2. Gradings of 3/4-in. maximum size aggregates.

Sieve size	Percent passing																
	A-F	A-P	A-I	A-4	A-4L(a)	A-8	A-8L(a)	A-30	A-30L(a)	A-100	A-100I	A-4H	A-4LH	A-8H	A-8LH	A-30H	A-30LH
3/4 in.	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1/2 in.	82	83	87	83	83	83	83	83	83	83	83	83	83	83	83	83	83
3/8 in.	71	73	77	73	54	73	73	73	73	73	73	73	64	73	73	73	73
No. 4	50	54	59	73	54	54	39	54	54	54	54	64	54	54	47	54	54
No. 8	35	39	45	39	39	54	39	39	21	39	39	39	39	47	39	39	30
No. 30	18	21	24	21	21	21	21	39	21	21	12	21	21	21	21	30	21
No. 50	13	15	17	15	15	15	15	15	15	21	12	15	15	15	15	15	15
No. 100	9	12	12	12	12	12	12	12	12	21	12	12	12	12	12	12	12
No. 200	6	8	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Grading	$P = 100 \frac{d}{D}^{0.50}$	$P = 100 \frac{d}{D}^{0.45}$	Iowa type A specs. 660	1/2-in.: No. 4 gap		No. 4-8 gap		No. 8-30 gap		No. 30-100 gap		(b)	(b)	(b)	(b)	(b)	(b)

Eight aggregate gradings were examined for 1/2-in. maximum size aggregates: a BPR maximum density grading (B-P); three BPR gradings with above-the-curve gaps between No. 4 and No. 8 sieves (B-8), between No. 8 and No. 30 sieves (B-30), and between No. 30 and No. 100 sieves (B-100); three BPR curves with below-the-curve gaps, B-4L, B-30L and B-100L; and a grading corresponding to the British Standard 594 hot rolled asphalt (B-B)[2,8]. These gradations are tabulated in Table 3 and plotted in Fig. 2a and Fig. 2b. Eight aggregate gradings were studied for 3/8-in. maximum size aggregates for all crushed limestones, including a BPR grading (C-P); three BPR curves with above-the-curve gaps between No. 4 and No. 8 sieves

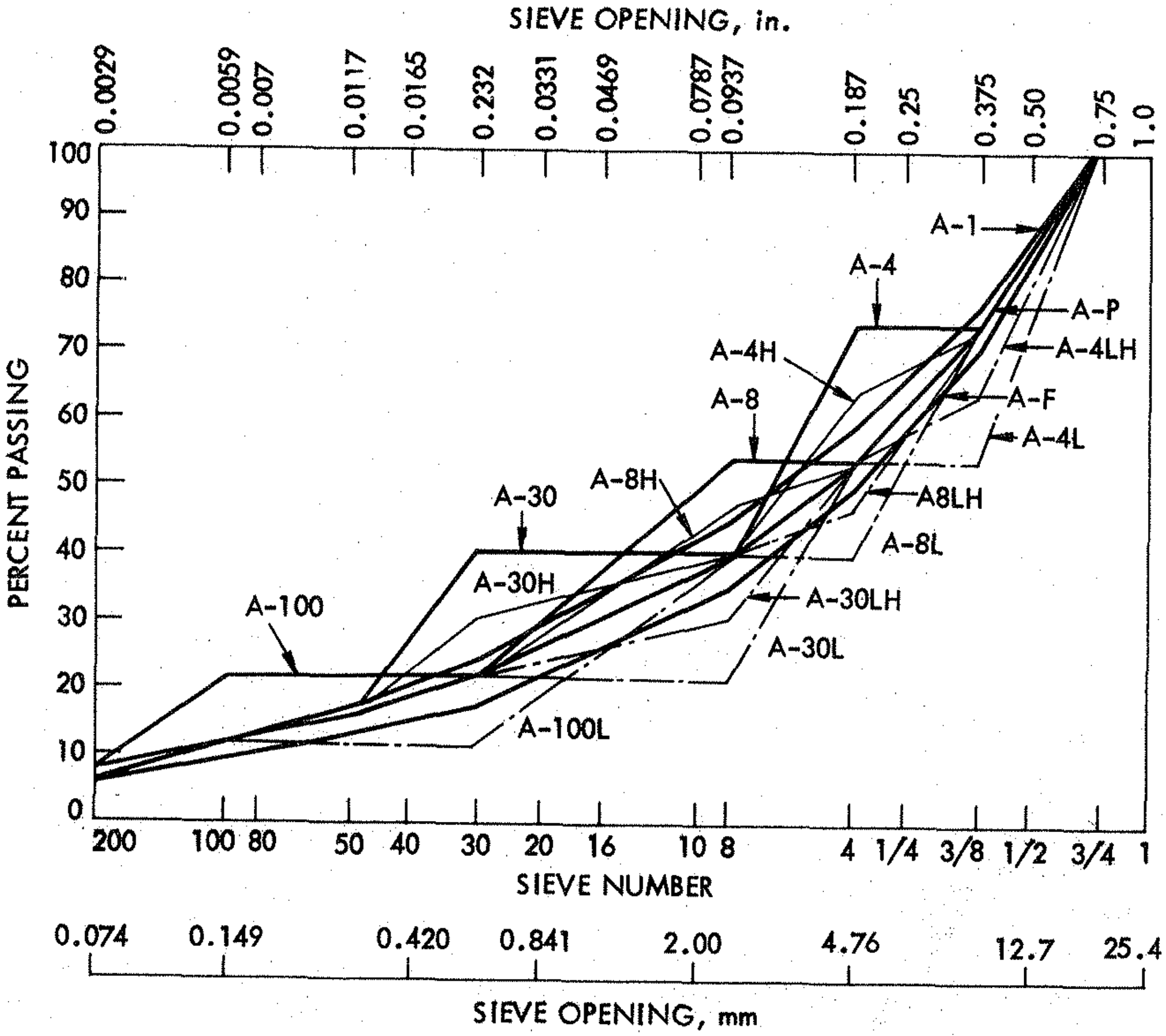

Fig. 1a. Grading curves for 3/4-in. maximum size aggregate.

(C-8), between No. 8 and No. 30 sieves (C-30), and between No. 30 and No. 100 sieves (C-100); and three BPR curves with below-the-curve gaps, C-8L, C-30L, and C-100L. Also included was a midpoint Iowa Type A grading (C-I). These gradations are shown in Table 4 and Figs. 3a and 3b.

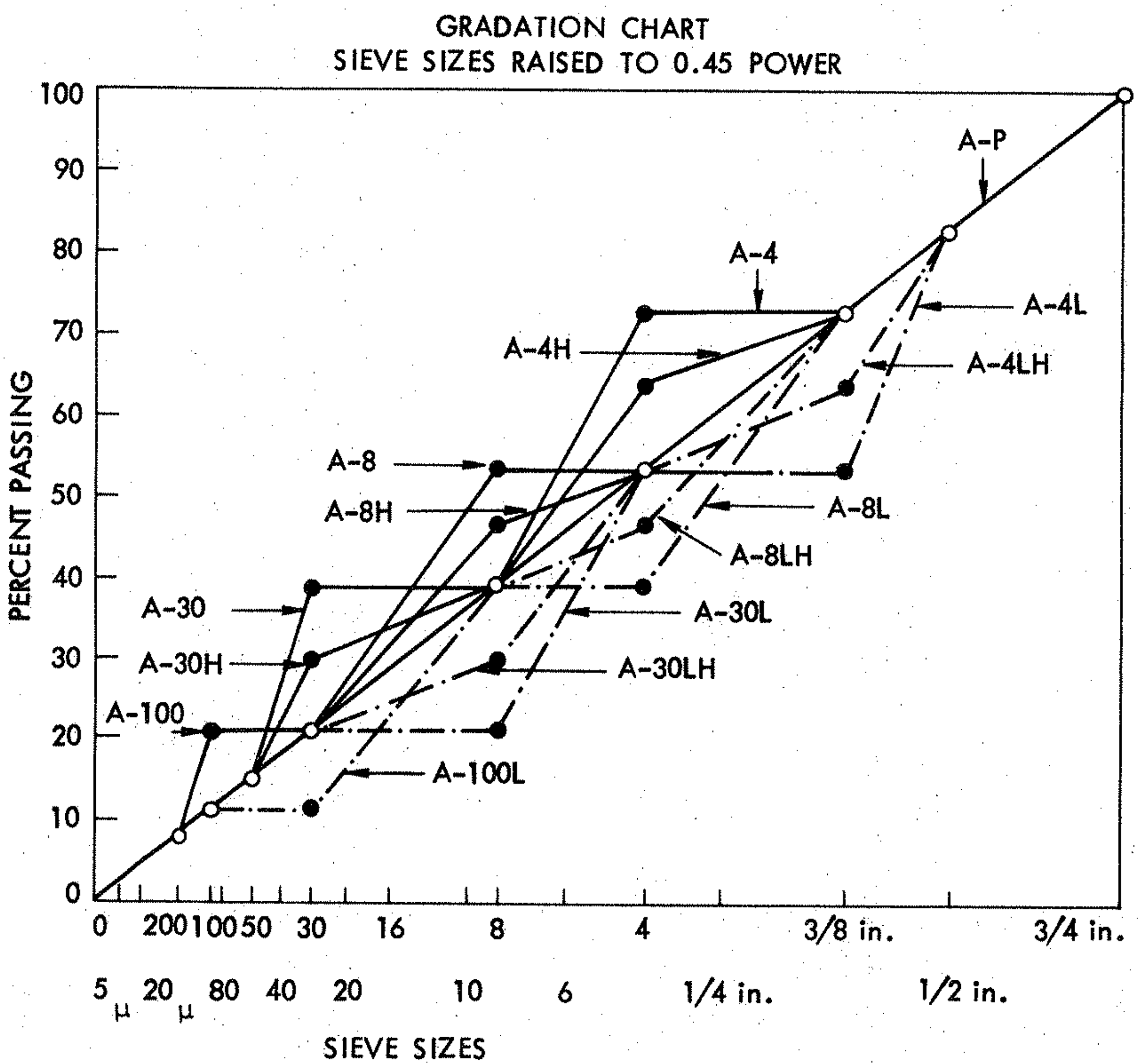

Fig. 1b. Grading curves for 3/4-in. maximum size aggregate.

<u>Asphalt Cements</u>

Three asphalt cements of two penetration grades were studied in conjunction with the above aggregate gradings. They were a 60-70 penetration and two 85-100 penetration. Asphalt A (65 pen.) was used in Series C and D; asphalt B (94 pen.) was used in Series A and B; and

Table 3. Gradings of 1/2-in. maximum size aggregates.

Sieve size	Percent passing							
	B-P	B-B	B-8	B-8L[a]	B-30	B-30L[a]	B-100	B-100L[a]
1/2 in.	100	100	100	100	100	100	100	100
3/8 in.	88	94	88	88	88	88	88	88
No. 4	64	73	64	47	64	64	64	64
No. 8	47	72	64	47	47	25	47	47
No. 30	25	62	25	25	47	25	25	14
No. 50	18	34	18	18	18	18	25	14
No. 100	14	21	14	14	14	14	25	14
No. 200	10	8	10	10	10	10	10	10
Grading	$P = 100 \frac{d}{D}^{0.45}$		B.S. 594		No. 4-8 gap	No. 8-30 gap	No. 30-100 gap	

[a]Gaps below B-P curves.

Asphalt C (91 pen.) was used in Series F. The characteristics of these asphalts are given in Table 5.

B. Experimental

Preliminary Laboratory Compaction Correlation

So that results obtained at the Iowa State University (ISU) Laboratory can be reproduced at the Iowa State Highway Commission (ISHC) Laboratory and so that valid comparisons may be made between mixtures compacted at

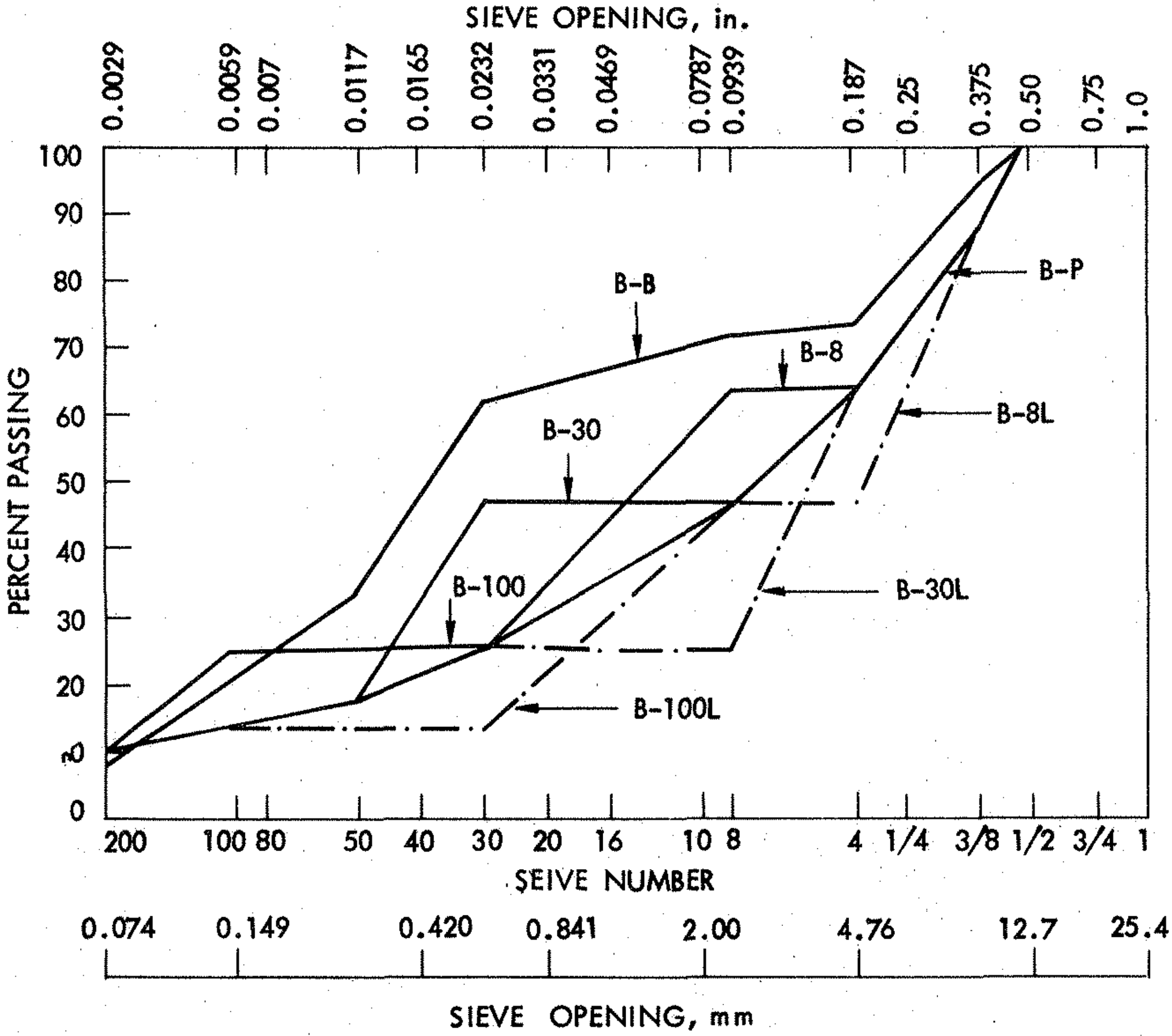

Fig. 2a. Grading curves for 1/2-in. maximum size aggregate.

the two places, a laboratory Marshall compaction correlation study was made, prior to commencing the primary studies (Part I and Part II).

Eight asphalt concrete plant mixes selected by Bernard C. Brown, Testing Engineer, ISHC, were used for this study. The mixes were asphalt treated base materials with a maximum size of aggregate of 3/4-in. The

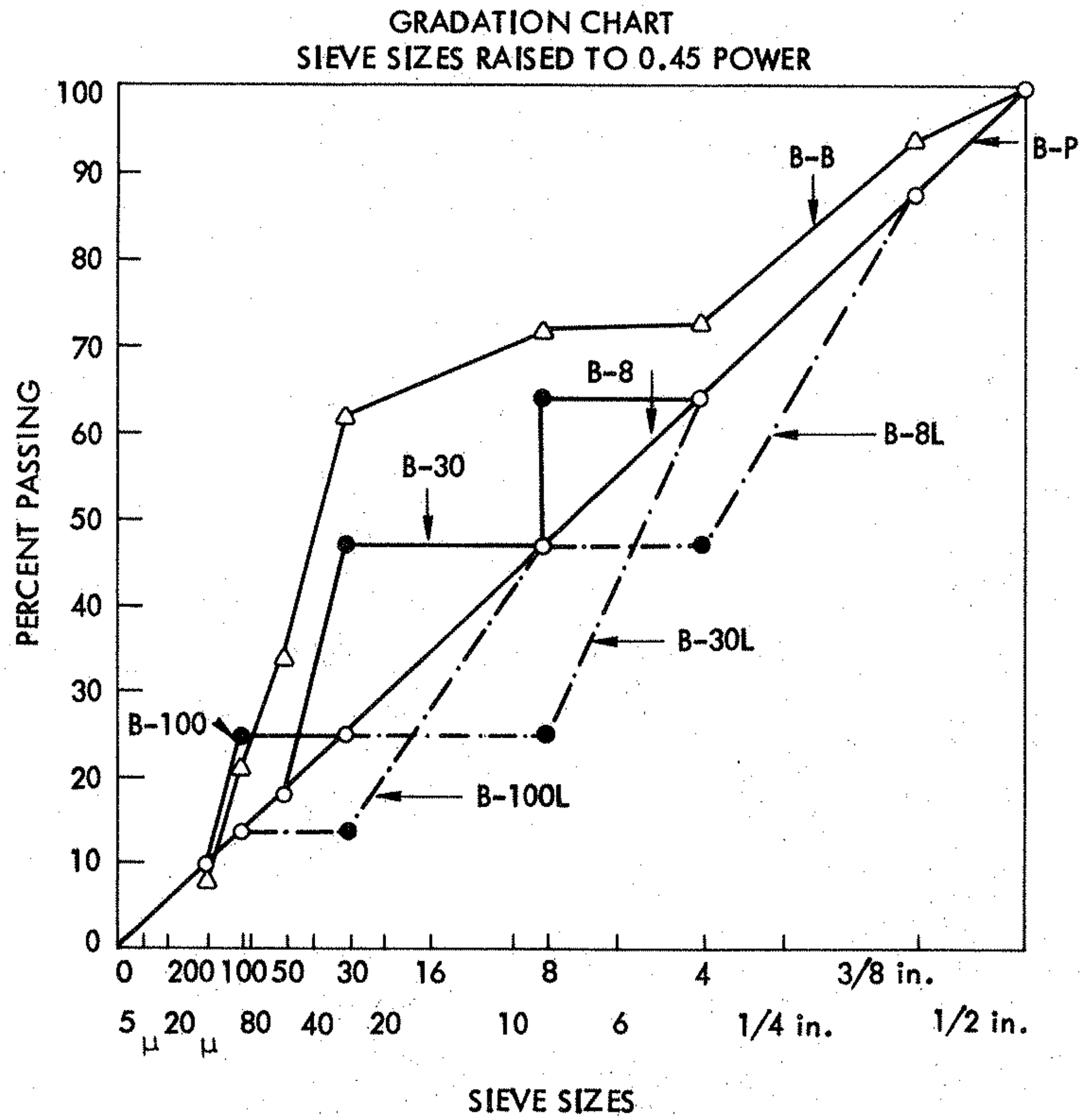

Fig. 2b. Grading curves for 1/2-in. maximum size aggregate.

mixes contained about 4 to 5% asphalt cement of 85-100 pen. The bulk specific gravity ranged from 2.13 to 2.37.

Two field samples of each mix were heated, combined, and resampled into two boxes (one for ISHC Lab and one for ISU Lab) at the ISHC Lab (Lab A). After a minimum cooling period of 24 hrs the samples were

Table 4. Gradings of 3/8-in. maximum size aggregates.

Sieve size	Percent passing							
	C-P	C-I	C-8	C-8L[a]	C-30	C-30L[a]	C-100	C-100L[a]
3/8 in.	100	100	100	100	100	100	100	100
No. 4	73	84	73	54	73	73	73	73
No. 8	54	62	73	54	54	29	54	54
No. 30	29	34	29	29	54	29	29	16
No. 50	21	22	21	21	21	21	29	16
No. 100	16	16	16	16	16	16	29	16
No. 200	11	9	11	11	11	11	11	11
Grading	$P = 100 \frac{d}{D} 0.45$	Iowa 660		No. 4-8 gap		No. 8-30 gap		No. 30-100 gap

[a]Gaps below C-P curves.

reheated and compacted, following Iowa Test Method No. 502-A (Appendix B); one Marshall specimen was selected for each mix in each of the four molds designated A, B, C, and D at each of the two laboratories. Sample heights were determined immediately after the hot extrusion and after the specimen had cooled to room temperature. Bulk specific gravities were determined in each laboratory on ALL specimens, following Iowa Test Method No. 503 A (Appendix C). A total of 68 specimens were compacted, including six additional cold extractions done at ISU Lab (Lab B).

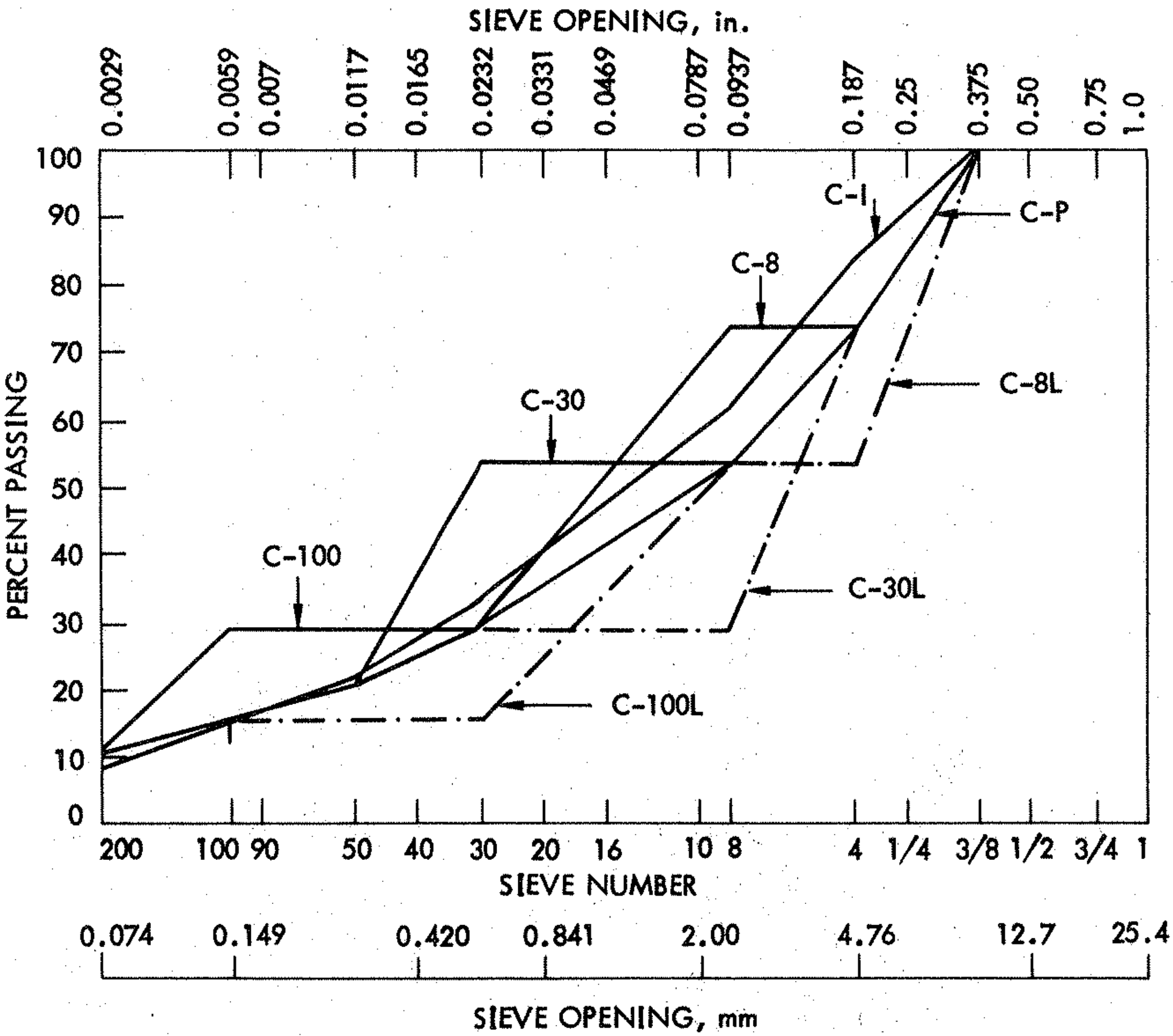

Fig. 3a. Grading curves for 3/8-in. maximum size aggregate.

Part I (Series A)

Objective

The purpose of Part I (Series A) of the experimental program was to evaluate the effect of five variables on the mechanical properties of asphalt concrete mixtures. These were: asphalt grade and content,

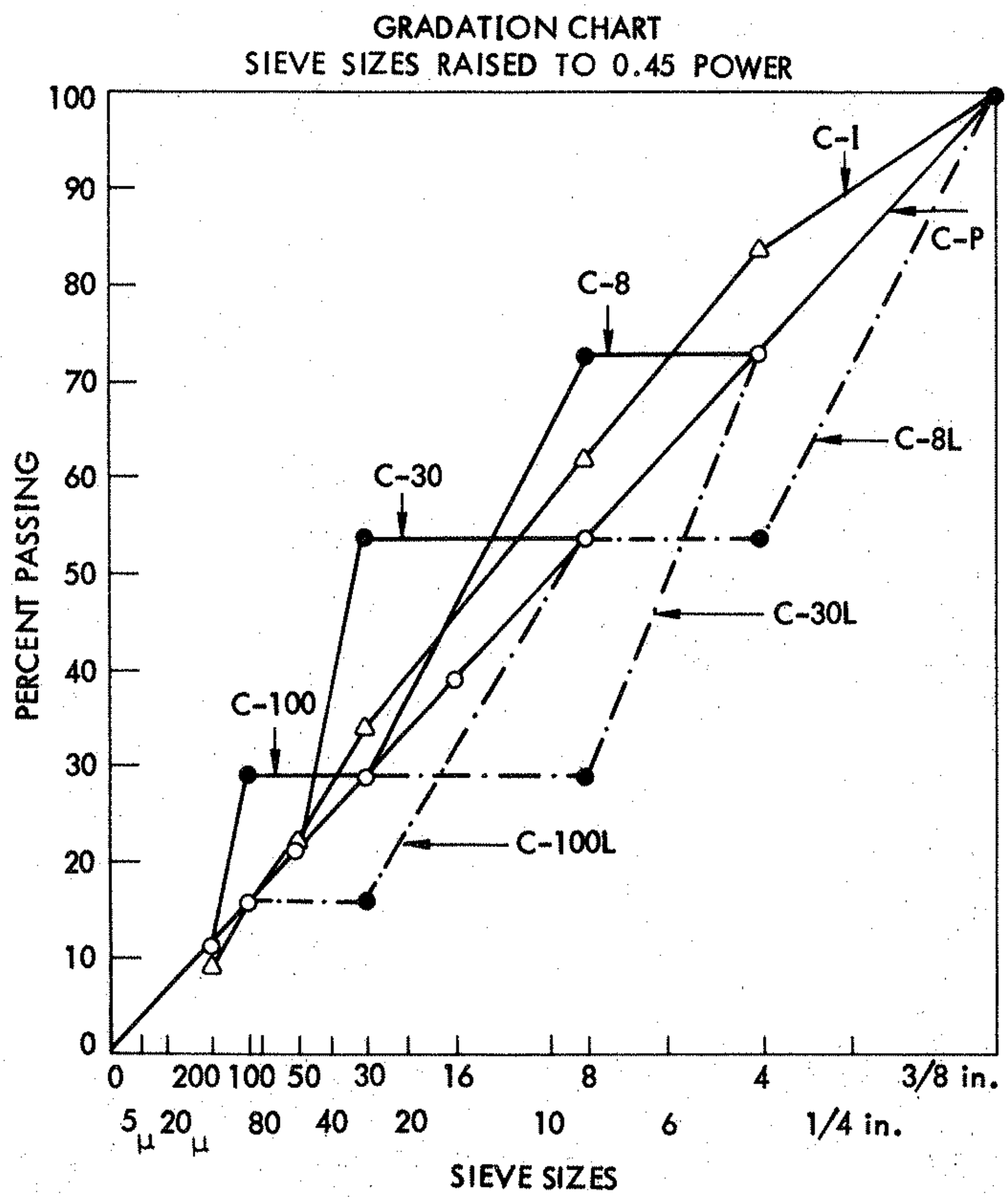

Fig. 3b. Grading curves for 3/8-in. maximum size aggregate.

aggregate type and gradation, and rate of compaction. Several related points also were examined, including:

- Investigation of the effect of removing "outlier" observations prior to conducting the statistical analysis;

Table 5. Characteristics of asphalts studied.

Property	Asphalt cements		
	157A	157B	157C
Penetration, 77/5/100	65	94	91
Viscosity at 77 ^{o}F, megapoises	7.50	1.26	0.82
Viscosity at 140 ^{o}F, poises	1985.98	1113.76	922.7
Viscosity at 275 ^{o}F, poises	383.50	337.22	237.02
T.F.O.T.			
% weight loss	0.0381	0.0430	+ 0.0156
Penetration of residue	36	53	55
Viscosity at 140 ^{o}F, poises	6142.37	2802.12	1922.4
Series	A,C,D	A,B	F

- Analysis of the response curve of strength (Marshall stability and flow) as a function of the percentage of asphalt content;
- Investigation of the optimum strength as a function of asphalt content and aggregate gradation.

Design

The variables and their respective levels are included in Part I and given in Table 6. A complete analysis of all main effects and all interactions of the five factors included in Table 6 would require 64 "batches" of material. A number of ways are available for reducing (fractioning) this experiment, using the usual design assumption that high order interactions (i.e., higher strength differences) are negligible. The design based on such a reduction (one half replicate) is as follows:

Table 6. Factors and levels included in Part I.

Factor	Levels
1. Aggregate type:	limestone (L_1); gravel (G)
2. Aggregate gradation:	BPR grading with max. size 3/4 in. (A-P)
	BPR grading with max. size 3/8 in. (C-P)
	gap 30 grading with max. size 3/4 in. (A-30)
	gap 30 grading with max. size 3/8 in. (C-30)
3. Asphalt grade:	60 pen.; 100 pen.
4. Asphalt content:	4%, 5%, 6%, 7%
5. Compactive effort:	50 blows; 75 blows

1. Prepare 32 batches based on a suitable half of the combinations of the two levels of aggregate type, gradation size and distribution, asphalt grade, and the four levels of asphalt content.

2. Sample 14 specimens from each batch, half of the 14 to be subjected to 50 blows and the other half to 75 blows.

Duplicate batches, in addition to providing an external error estimate, were used to compare the effects of the type of extraction (hot, air cool, water cool), and the time between specimen preparation and testing (1 day, 2-4 weeks, 6 months, 1 year) on the stability measurements.

Based on a one-half replicate of a $2^3 \times 4^2$ factorial design plus four duplicate batches for the external error estimate, a total of 36 batches (40 lb each) of asphalt concrete mixtures were made, following the schedule in Table 7. The mixing and compaction procedures are given in Appendix D.

Table 7. Factor combinations and batch scheduling for Series A, Part I.

Code			Experimental conditions					
Batch	Compaction	Specimen	Type	Gradation	Asphalt grade	Asphalt content	Compactive blows	Extraction and time of testing
001	1	1-7	L	C-P	100	8	50	2-h
001	2	1-7					75	
002	2	1-7	G	A-P	100	6	75	
002	1	1-7					50	
003	2	1-7	G	A-P	60	4	75	
003	1	1-7					50	
004	2	1-7	G	A-30	100	5	75	
004	1	1-7					50	
005	1	1-7	G	C-P	60	7	50	
005	2	1-7					75	
006	1	1-7	G	C-30	60	7	50	
006	2	1-7					75	
007	2	1-7	L	C-30	60	6	75	
007	1	1-7					50	
008	2	1-7	L	C-30	100	5	75	
008	1	1-7					50	
009	2	1-7	L	C-30	60	4	75	
009	1	1-7					50	
010	2	1-7	G	C-P	100	6	75	
010	1	1-7					50	
011	2	1-7	G	C-30	100	6	75	
011	1	1-7					50	
012	2	1-7	L	A-30	60	5	75	
012	1	1-7					50	
013	2	1-7	G	C-P	100	4	75	
013	1	1-7					50	
014	1	1-7	L	A-30	100	4	50	
014	2	1-7					75	
015	1	1-7	L	A-P	100	4	50	
015	2	1-7					75	
016	1	1-7	G	A-30	60	4	50	
016	2	1-7					75	
017	2	1-7	L	A-P	60	5	75	
017	1	1-7					50	
018	1	1-7	L	A-30	60	7	50	
018	2	1-7					75	
019	1	1-7	G	C-P	60	5	50	
019	2	1-7					75	
020	2	1-7	G	C-30	100	4	75	
020	1	1-7					50	
021	1	1-7	G	A-30	60	6	50	
021	2	1-7					75	
022	2	1-7	L	C-P	60	6	75	
022	1	1-7					50	
023	2	1-7	L	C-P	100	5	75	
023	1	1-7					50	
024	1	1-7	G	A-30	100	7	50	
024	2	1-7					75	
025	2	1-7	L	A-P	100	6	75	
025	1	1-7					50	
026	1	1-7	L	C-P	60	4	50	
026	2	1-7					75	
027	2	1-7	L	C-30	100	7	75	
027	1	1-7					50	
028	1	1-7	L	A-P	60	7	50	
028	2	1-7					75	
029*	1	1-4	L	A-30	100	6	50	2-h
029	1	5					50	4-a
029	1	6					50	3-a
029	1	7					50	1-a

(Time of stability test: 1: 1 day after compaction; 2: regular (3 days); 3: 180 days after compaction; 4: 360 days after compaction)

(Extraction: h – hot extraction; a – air cooled extraction; w – water cooled extraction)

Table 7. Continued.

Code			Experimental conditions					Extraction and time of testing
Batch	Compaction	Specimen	Type	Gradation	Asphalt grade	Asphalt content	Compactive blows	
029	2	1-4	L	A-30	100	6	75	2-h
029	2	5					75	4-w
029	2	6					75	1-w
029	2	7					75	3-w
030	2	1-4	G	A-P	60	6	75	2-h
030	2	5					75	3-w
030	2	6					75	1-w
030	2	7					75	4-w
030	1	1-4	G	A-P	60	6	50	2-h
030	1	5					50	4-a
030	1	6					50	1-a
030	1	7					50	3-a
031	1	1-4	L	A-30	100	6	50	2-h
031	1	5					50	3-w
031	1	6					50	1-w
031	1	7					50	4-w
031	2	1-4	L	A-30	100	6	75	2-h
031	2	5					75	1-a
031	2	6					75	3-a
031	2	7					75	4-a
032a	2	1-3	G	C-30	60	5	75	2-h
032	2	4					75	3-a
032	2	5					75	4-w
032	2	6					75	4-a
032	2	7					75	3-w
032	1	1-3	G	C-30	60	5	50	2-h
032	1	4					50	3-a
032	1	5					50	4-w
032	1	6					50	3-w
032	1	7					50	4-a
033a	1	1-4	G	A-P	60	6	50	2-h
033	1	5					50	1-w
033	1	6					50	4-w
033	1	7					50	3-w
033	2	1-4	G	A-P	60	6	75	2-h
033	2	5					75	4-a
033	2	6					75	3-a
033	2	7					75	1-a
034	1	1-5	G	C-30	60	5	50	2-h
034	1	6					50	1-w
034	1	7					50	1-a
034	2	1-5	G	C-30	60	5	75	2-h
034	2	6					75	1-w
034	2	7					75	1-a
035a	1	1-3	G	A-P	100	7	50	2-h
035	1	4					50	1-w
035	1	5					50	1-a
035	1	6					50	4-a
035	1	7					50	4-w
035	2	1-3	G	A-P	100	7	75	2-h
035	2	4					75	3-w
035	2	5					75	4-a
035	2	6					75	4-w
035	2	7					75	3-a
036	1	1-5	G	A-P	100	7	50	2-h
036	1	6					50	3-w
036	1	7					50	3-a
036	2	1-5	G	A-P	100	7	75	2-h
036	2	6					75	1-w
036	2	7					75	1-a

(a) Duplicates.

The experimental design outlined above will allow analysis of both main effects (effect of a single variable on strength) and interactions (joint effects of two or more variables). The effects and interactions to be measured in this experiment are listed in Table 8. All other interactions are assumed negligible.

It is expected that through such an analysis the significance of the five factors can be tested and the variables influencing the Marshall properties of asphalt-cement mixtures can be identified.

Such significance testing will require measures of experimental error. In this experiment, two such measures will be involved: the first incorporating experimental variability in the preparation of batches, the other reflecting residual experimental variability, once a batch is formed.

It will be possible to compute these two measures of experimental error in three different ways, thus allowing for a consistency check. The first of these is the "external" estimate based on the five replicates mentioned above. The second is based on "high-order" interactions in Table 8, and the third involves graphical "half-normal plotting."

Part II (Series B, C, D, and F)

Objectives

The purpose of Part II of the experimental program is to evaluate in more detail the effect on the mechanical properties of asphalt-concrete mixtures of two of the variables: aggregate gradation and asphalt content. Also, a more extensive investigation is planned for the relationship of these two variables to the simultaneous strength-maximizing blend of aggregate and asphalt.

Table 8. Factors and interactions to be analyzed.

Main effects	Two-factor interactions		
A. Aggregate type	AB	BD	CE
B. Gradation (size)	AC	Bα	Dα
C. Gradation (distribution)	AD	Bβ	Dβ
D. Asphalt grade	Aα	Bγ	Dγ
E. Compactive effort	Aβ	BE	DE
α. Linear asphalt content effect	Aγ	CD	Eα
β. Quadratic asphalt content effect	AE	Cα	Eβ
γ. Cubic asphalt content effect	BC	Cβ	Eγ
		Cγ	

Three-factor interactions			Four-factor interactions
ABβ	ACE	BEα	ABEβ
ACβ	ADG	BEY	ACEβ
BCβ	AEβ	CDE	BCEβ
ADβ	AEα	CEβ	ADEβ
BDβ	AEY	CEα	BDEβ
CDβ	BCE	CEY	CDEβ
ABE	BDE	DEβ	
	BEβ	DEα	
		DEY	

Design

The original planned experiment would have required the preparation of 330 batches, based on all combinations of the levels of the factors listed in Table 9 (660 batches of two asphalt cements are used). After completion of Series A, it was felt that a 60-pen. asphalt should be included in the study and that desired information and interactions could be obtained without making complete factor combinations (660 batches). Experimental design was made for Part II to include:

Series B, $L_1 \times$ Asphalt B, 165 batches (Table 10a)

Series C, $L_1 \times$ Asphalt A, 85 batches (Table 10b)

Series D, $L_2 \times$ Asphalt A, 85 batches (Table 10b)

Series E, $L_2 \times$ Asphalt B, 85 batches (Table 10b)

Series F, Gravel $\times$ Asphalt B, 45 batches (Table 10c)

making a total of 465 batches. For reasons discussed in Progress Report No. 5 and in Vol. II of this report, Series E (85 batches) was eliminated from the investigation, making a total of 380 batches in Part II.

Nine specimens were prepared from each batch. Six specimens were compacted by the Marshall method and three specimens by the Hveem method. Of the six Marshall specimens, three were tested following the standard Marshall method and two were tested by the Marshall immersion compression[26,27].

Analysis

The experiment, as designed, allowed evaluation of all main effects and interactions of the variables included in the experiment for each design method. Of particular interest was the comparison of the conventional and gap gradation distributions. The effects tested are summarized in Table 11.

Table 9. Factors and levels included in Part II.

1. Aggregate type:	Limestone: L1; L2
2. Aggregate gradation:[a]	A-F, A-P, A-I, A-4, A-4L, A-8, A-8L, A-30 A-30L, A-100, A-100L, A-4H, A-4LH, A-8H, A-8L-H, A-30H, A-30LH B-P, B-B, B-8, B-8L, B-30, B-30L B-100, B-100L C-P, C-I, C-8, C-8L, C-30, C-30L C-100, C-100L
3. Asphalt grade:[b]	60 pen.; 100 pen.
4. Asphalt content:	3%, 4%, 5%, 6%, 7%, (8%)
5. Compaction:[c]	Marshall 50 and Hveem kneading

[a] Paired symbols refer respectively to the maximum size (A: 3/4 in., B: 1/2 in., C: 3/8 in.), and to size distribution (F: Fuller's curve, P: Bureau of Public Roads curve, I: Iowa Highway Commission curve, 4: gap 4, 8: gap 8, 30: gap 30, 100: gap 100, L: below-the-curve-gap, and H: half gap).

[b] A decision to include the two different asphalt grades will depend on how significant this factor is in influencing asphalt-concrete strength. Otherwise, the experiment will include only grade 100 pen.

[c] Two thirds of the mixture will be compacted by the Marshall method, and one third by the Hveem method.

C. Methods and Procedures

Mixing and Compaction

Oven dried crushed aggregates were first separated by 3/4-in., 1/2-in., 3/8-in., No. 4, No. 8, No. 30, No. 50, No. 100, and No. 200 sieves.

Table 10b. Batch scheduling — series[a] C, D and E, Part II.

	C		D		E	
Batch No.	L_1, 60 pen., wt. %		L_2, 60 pen., wt. %		L_2, 100 pen., wt. %	
001-005	C-100L:	6,5,3,7,4	A-I:	6,4,7,3,5	B-100:	5,6,3,7,4
006-010	B-P:	7,6,3,4,5	C-I:	4,5,7,3,6	A-4LH:	6,3,4,5,7
011-015	B-B:	4,7,5,6,3	B-8:	3,4,5,6,7	A-100L:	6,4,5,3,7
016-020	A-4:	6,4,3,7,5	B-30:	6,4,5,3,7	A-F:	7,4,6,3,5
021-025	A-100:	4,6,5,7,3	A-30L:	3,5,6,4,7	C-30:	3,5,7,6,4
026-030	A4LH:	5,4,7,3,6	C-100:	5,4,7,6,3	B-B:	4,6,7,5,3
031-035	A-8L:	7,6,4,3,5	A-8LH:	4,6,7,3,5	B-100L:	6,4,5,3,7
036-040	B-100L:	5,3,4,7,6	C-100L:	3,5,7,4,6	A-8L:	7,5,3,4,6
041-045	A-30H:	4,6,7,5,3	C-P:	7,6,4,3,5	A-8:	7,5,6,3,4
046-050	A-8:	4,5,7,3,6	B-30L:	7,4,5,6,3	A-4:	7,4,6,3,5
051-055	B-100:	7,4,3,5,6	C-8L:	5,4,3,6,7	B-P:	7,6,3,5,4
056-060	C-30L:	3,5,6,4,7	A-4H:	4,7,6,5,3	B-8L:	4,6,3,7,5
061-065	C-8:	3,6,7,5,4	A-4L:	3,6,5,7,4	A-100:	6,5,7,4,3
066-070	A-F:	5,3,6,7,4	A-8H:	4,5,7,6,3	A-30H:	5,4,7,3,6
071-075	B-8L:	5,4,3,7,6	A-30LH:	4,6,5,7,3	C-8:	4,6,3,5,7
076-080	A-100L:	6,5,3,7,4	A-P:	7,4,5,6,3	C-30L:	5,6,7,3,4
081-085	C-30:	5,7,4,6,3	A-30:	3,7,4,5,6	C-100L:	7,6,5,4,3

[a] Aggregates L_1 = Ferguson limestone; L_2 = Moscow limestone.
Asphalt cements: 60 = 60-70 pen. = asphalt A;
100 = 85-100 pen. = asphalt B.

Table 10a. Batch scheduling — Series B, Part II (HR-157)[a].

Batch No.	Gradation	% A.C. by wt. of aggregate
B-001-05	B-8	6,3,4,5,7
06-10	A-30H	6,4,3,7,5
11-15	B-P	3,5,6,7,4
16-20	C-100	3,4,7,5,6
21-25	C-100L	6,7,4,3,5
26-30	B-30	7,5,6,4,3
31-35	A-30L	5,3,7,6,4
36-40	A-8	5,4,6,3,7
41-45	A-I	7,6,3,4,5
46-50	A-30LH	5,4,7,3,6
51-55	A-F	4,5,6,3,7
56-60	C-I	3,7,4,6,5
61-65	A-8LH	5,7,4,6,3
66-70	A-30	6,5,4,3,7
71-75	A-4L	7,5,4,3,6
76-80	A-4LH	3,7,5,6,4
B-081-085	A-8H	3,6,7,5,4
086-090	B-8L	4,3,7,5,6
091-095	B-30L	5,7,3,6,4
096-100	C-P	6,3,4,5,7
101-105	B-B	3,4,7,6,5
106-110	A-8L	4,3,6,7,5
111-115	B-100L	4,3,7,6,5
116-120	C-8L	3,7,4,6,5
121-125	A-4H	3,5,6,4,7
126-130	B-100	5,6,3,7,4
131-135	C-8	6,7,4,5,3
136-140	A-100L	7,4,6,5,3
141-145	A-4	7,4,6,3,5
146-150	C-30L	6,4,3,7,5
151-155	A-P	6,5,7,4,3
156-160	C-30	3,5,7,6,4
161-165	A-100	4,6,5,7,3

[a] Aggregate: LI (Ferguson); A.C.: B (85-100 pen.).

Table 10c. Batch scheduling — Series F, Crushed gravel and natural gravel.

Batch No.	Gradation	Asphalt content, wt. % of aggregate
F 001 - 005	A-4	6,4,3,7,5
F 006 - 010	A-4L	3,6,5,7,4
F 001 - 015	A-8	4,5,7,3,6
F 016 - 020	A-8L	7,5,3,4,6
F 021 - 025	A-30	3,7,4,5,6
F 025 - 030	A-30L	5,3,7,6,4
F 031 - 035	A-100	3,4,6,7,5
F 036 - 040	A-100L	6,5,3,7,4
F 041 - 045	Natural gravel	3,4,5,6,7

Concrete sand was separated and added to retain No. 30 and No. 50 fractions at a 50-50 ratio. Required weights of each fraction were then combined to produce gradation curves in Figs. 1 through 3. Asphalt concrete mixtures were made in a 50-lb laboratory pug-mill mixer at asphalt contents from 4 to 8%. A total of 36 batches of mixes of 40 lb each were made in Part I (Series A) and a total of 380 batches of 28 lb each were made in Part II. The detailed mixing and compaction procedures are given in Appendix D, except that in Part II, nine specimens were prepared instead of 14, and the specimens were designated by five-digit numbers: x-xxx-x. The first digit represents the series identification (B, C, D, and F), the second three digits are batch numbers, the fifth digit is the specimen number (1-9). Specimens 1-6 were Marshall 50 blows

Table 11. Analysis of variance in Part II.

Effect	d.f.	
Batches		
Main effects	37	
(G) Gradation		32
(C) Asphalt content		4
(A) Aggregate type		1
2-factor interactions	164	
GC		128
GA		32
CA		4
3-factor interactions, GCA	128	
Batch error		
Specimen within batches		
(D) Compaction	1	
2-factor interactions	37	
DG		32
DC		4
DA		1
3-factor interactions	164	
DGC		128
DGA		32
DCA		4
4-factor interaction, DGCA	128	
Specimen error		
Total	659	

and specimens 7-9 were prepared by the standard Hveem method. The series of mixes were prepared following alphabetical order; batching sequence within each series followed the numerical order as presented in the batching schedule tables. A five-batches-per-day schedule was followed throughout the mixing-compaction period. Because of the limited amounts of passing No. 50 fractions available in the quarry-crushed aggregates, it was necessary to pulverize some retained No. 8 fractions in a laboratory screen mill to produce sufficient fines needed in the project.

Testing

Compacted specimens were tested for sample height and bulk specific gravity (Appendix C and ASTM-D2726) the next day. Except for Series A specimens for which the Marshall stability and flow were determined (following a strict time schedule of 1 day, 3 days, 180 days, and 360 days), the specimens were tested for Marshall stability at 140 ^{o}F (ASTM D-1559) on a Pine 900 Recording Tester , for Hveem stability and cohesion at 140 ^{o}F (ASTM D-1560), and for Rice maximum specific gravity (ASTM D-2041) within two weeks of compaction.

Indirect tensile strength at 77 ^{o}F and at a rate of strain of 2 in. per min on specimens No. 6 were tested during the last quarter of the project, following the procedure in Appendix E. The set-up of the indirect tensile test (ITT) is shown in Figs. 4a and 4b.

The indirect tensile strength (T) is calculated from the maximum load (P) by the following formula:

$$T = \frac{2P}{\pi t d}$$

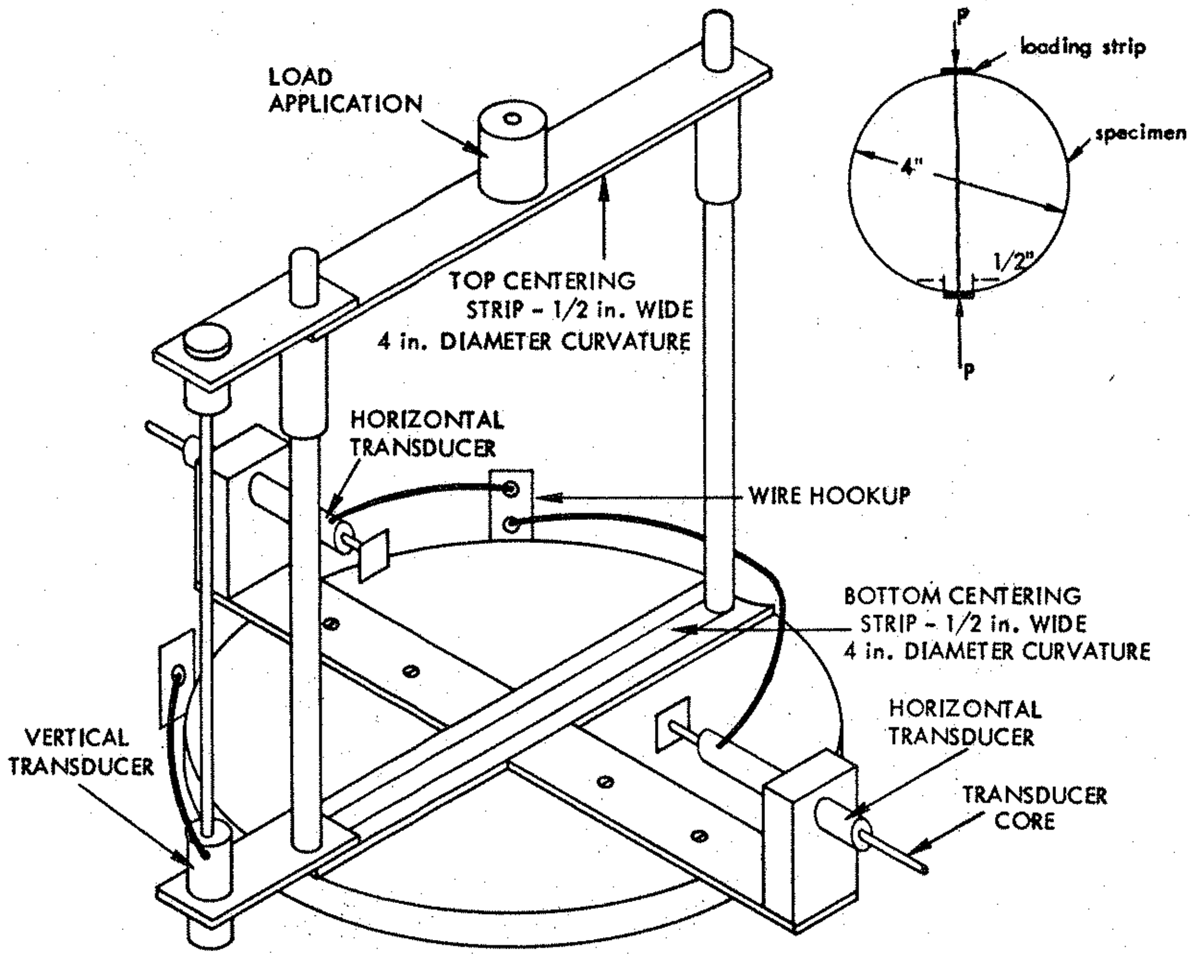

Fig. 4a. Indirect tensile test set-up.

where

P = maximum total load, lb,

t = thickness of the specimen, in., and

d = nominal diameter of the specimen = 4 in.

Calculations and Graphing

The Marshall stability and flow were read off the recording chart paper and corrected for specimen height. The Hveem stability and cohesion were determined on the same specimen, following standard procedure[28].

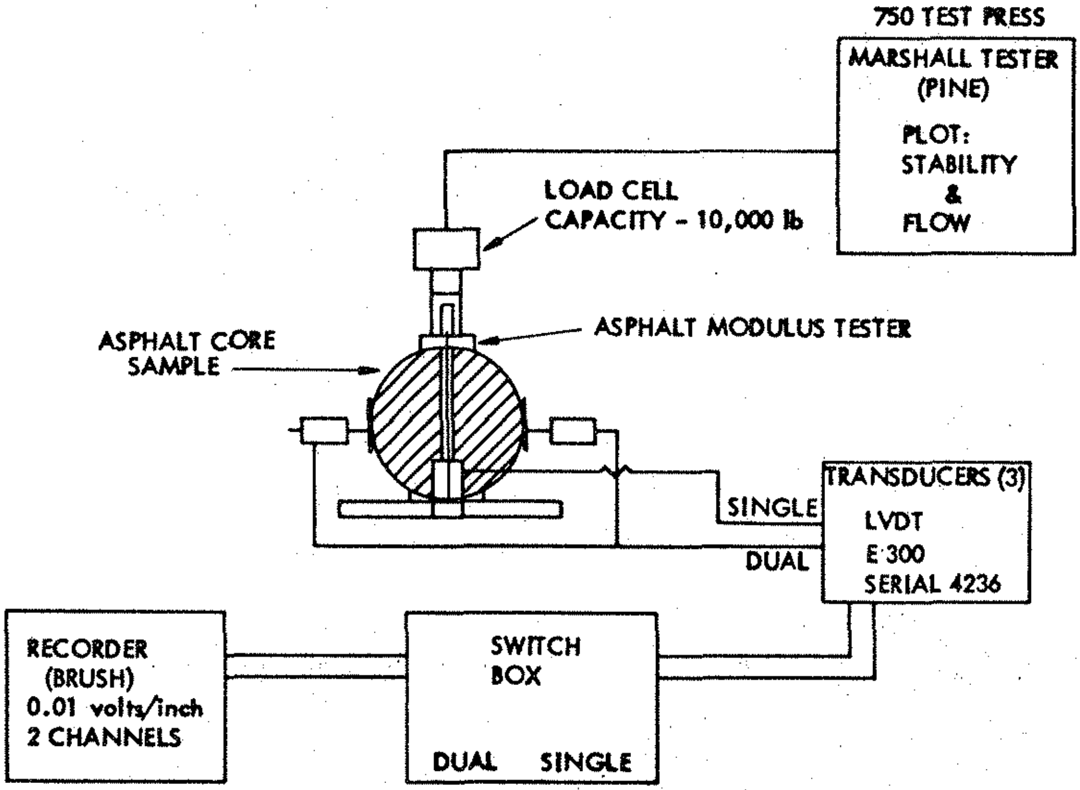

Fig. 4b. Indirect tensile test system flow diagram.

For certain plastic mixes, e.g., B001, during the stability test, the horizontal pressure exceeded 100-120 psi before the vertical pressure reached 400 psi, and the test was stopped to prevent damage to the rubber diaphragm of the stabilometer. In these cases the horizontal pressures P_h corresponding to the vertical pressure of 400 psi were extrapolated from log P_h vs log P_v plots and were used to calculate the relative stability values. There were also cases that, while more plastic mixes were encountered, e.g., C-22, the specimens could not be removed from the stabilometer without being destroyed; in these cases, there are no cohesion values recorded.

The percentage of air voids in the compacted specimens (V_v) was determined from the bulk specific gravity of the specimen (G_{mb} or d) and the Rice theoretical maximum specific gravity (G_{mm} or D), by the following equation:

$$V_v, \% = \left(\frac{G_{mm} - G_{mb}}{G_{mm}}\right) \times 100 .$$

The voids in the compacted mineral aggregates (VMA) were determined by the following equation:

$$\text{VMA}, \% = 100 - \frac{(P_{ag} \times G_{mb})}{G_{ag}}$$

where: P_{ag} = percentage of aggregate by weight of total mix

G_{ag} = average ASTM bulk specific gravity of the total aggregate in the mix.

Eight graphs were plotted from each series of five batches, (combinations of aggregate type, asphalt type and gradation) at five asphalt contents for Marshall specimens: original stability vs asphalt content; original flow vs asphalt content, bulk specific gravity (unit weight) vs asphalt content, air voids vs asphalt content, VMA vs asphalt content, tensile strength vs asphalt content, 24-hr immersion stability vs asphalt content and 24-hr immersion flow vs asphalt content. Sample plots of these are shown in Figs. 5a to 8a. For the same five batches of mixes, five Hveem property curves were plotted, with stability, cohesion, bulk specific gravity (unit weight), air voids and VMA as ordinates and asphalt content as abscissa. Sample plots of these curves are shown in Figs. 5b to 8b.

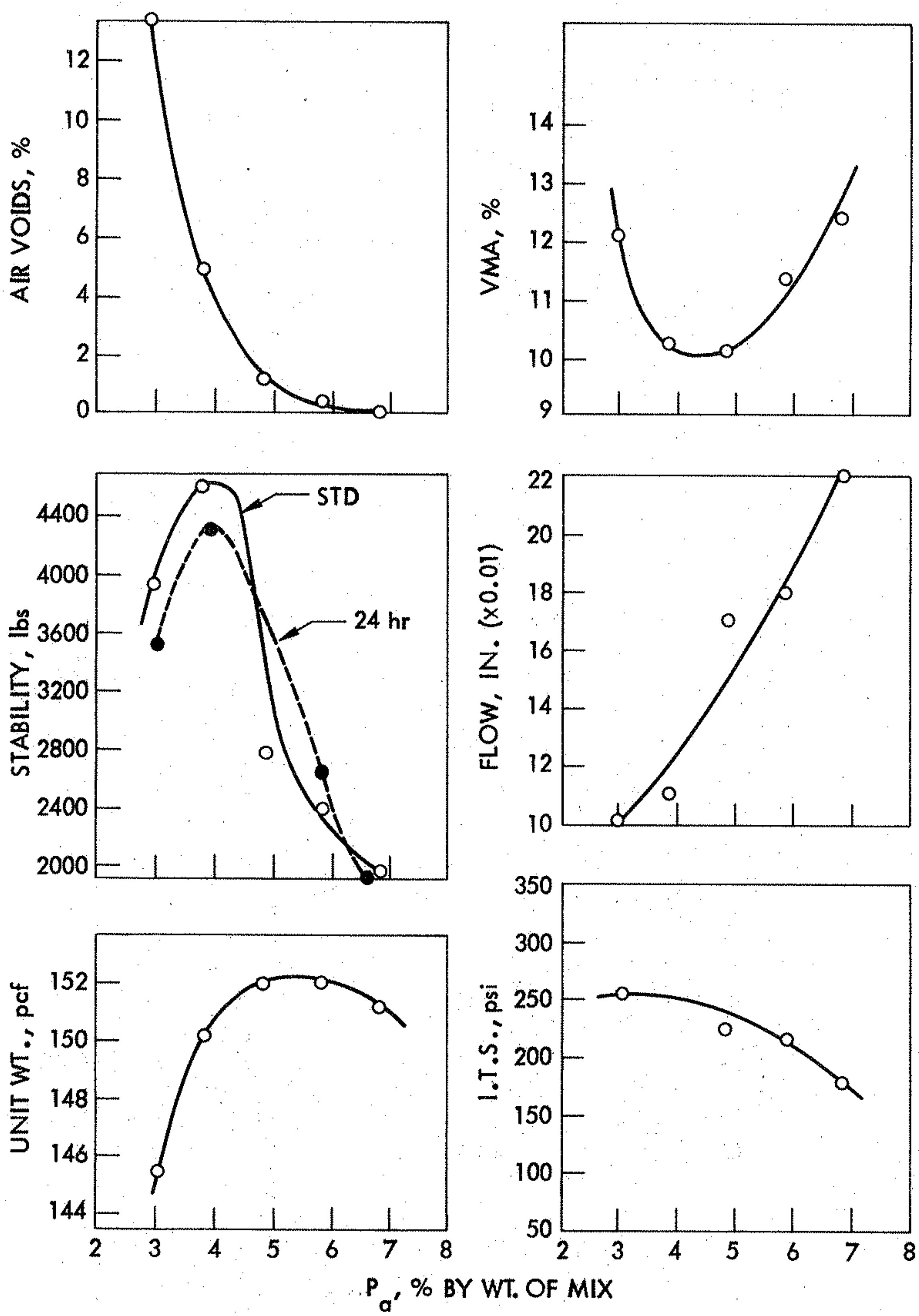

Fig. 5a. Typical Marshall property curves, B-026-030 (B-30).

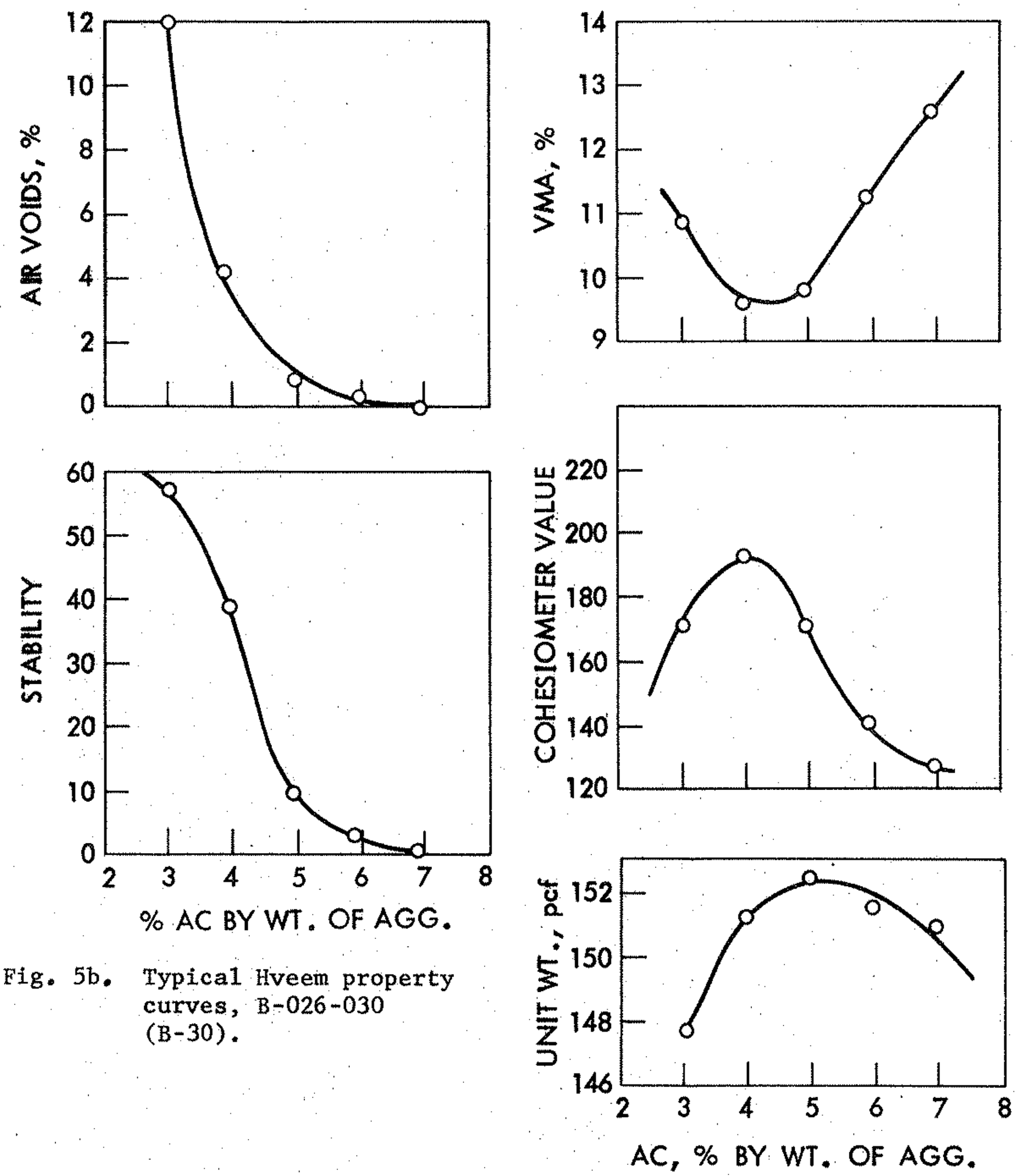

Fig. 5b. Typical Hveem property curves, B-026-030 (B-30).

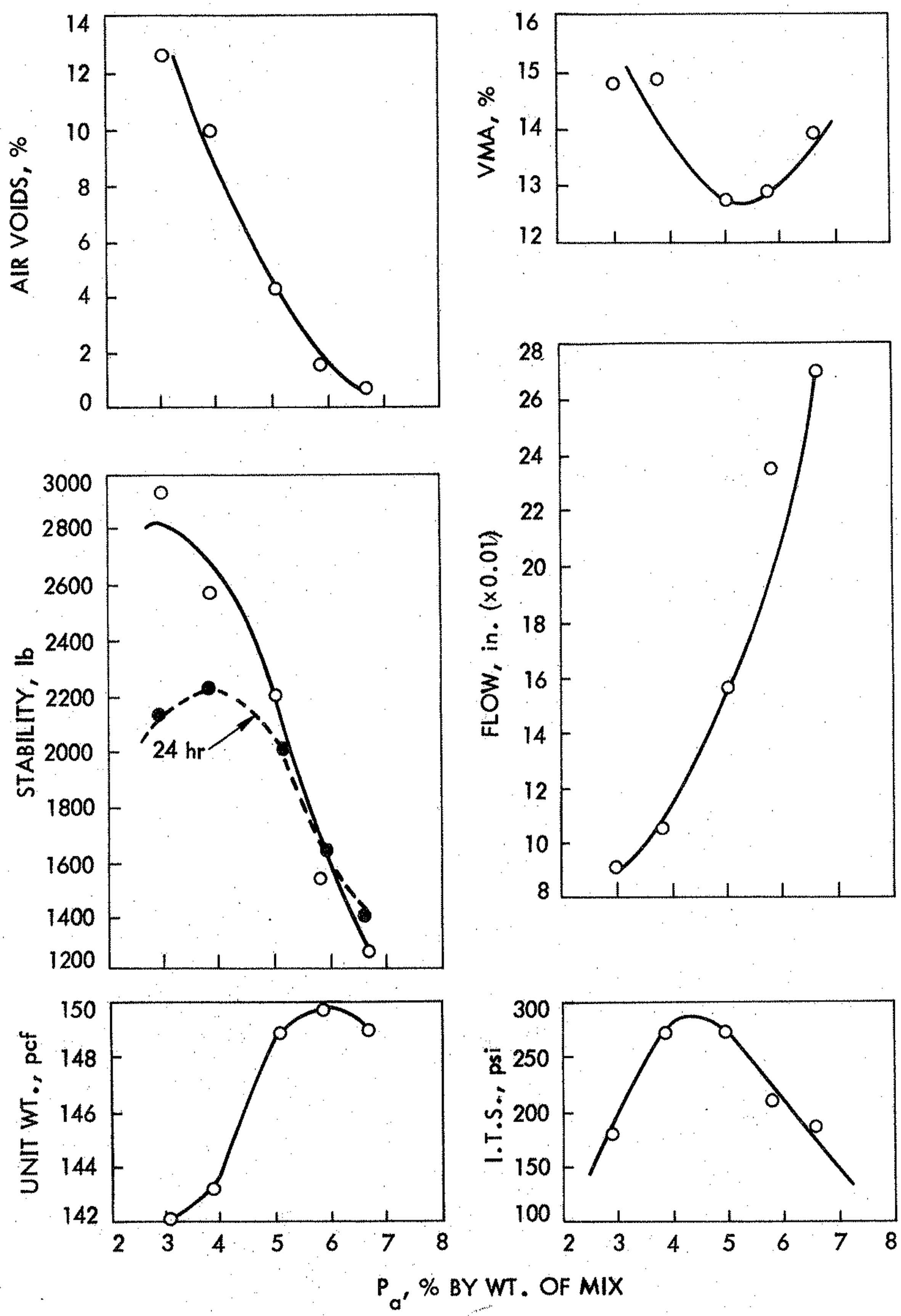

Fig. 6a. Typical Marshall property curves, C051-055 (B-100).

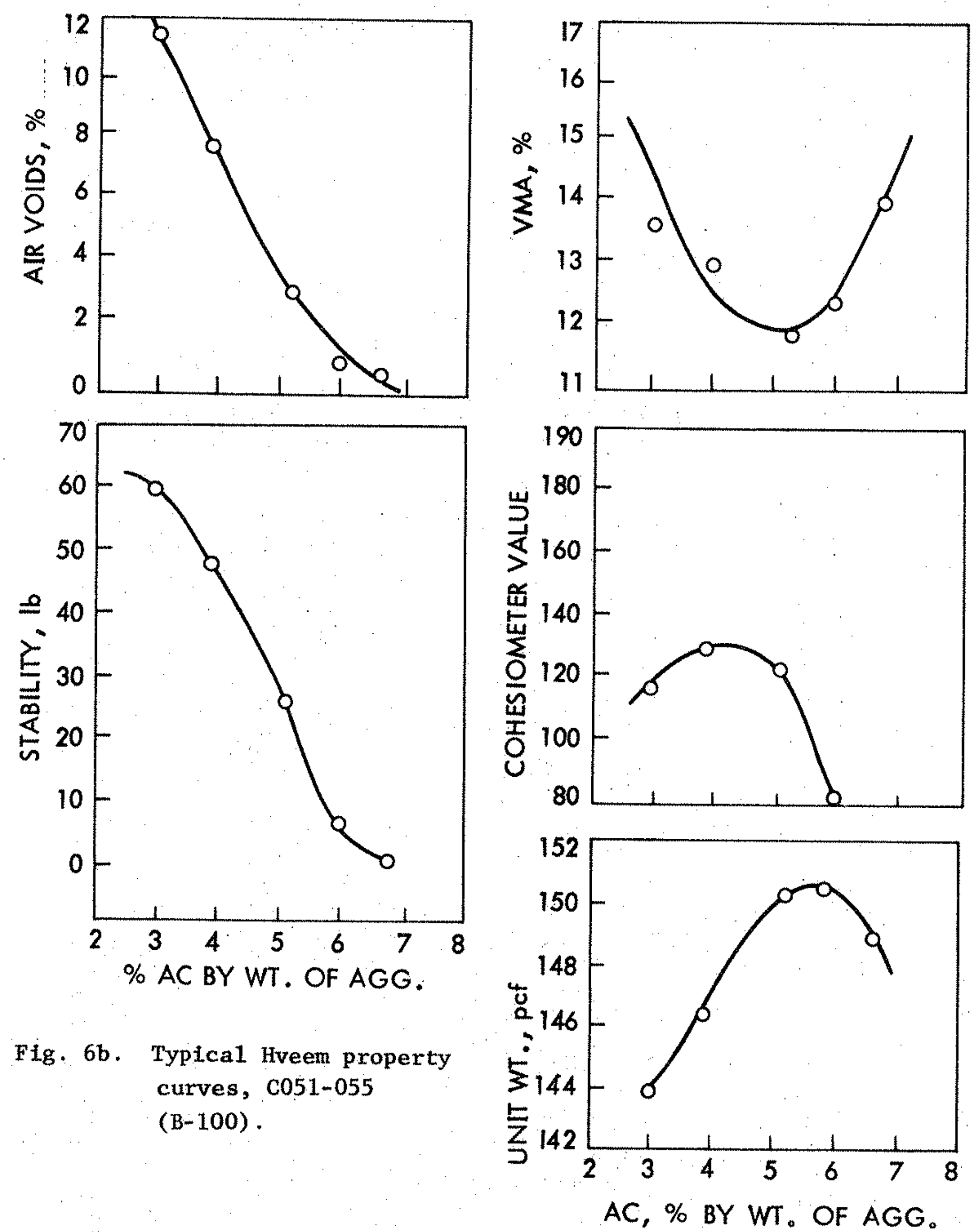

Fig. 6b. Typical Hveem property curves, C051-055 (B-100).

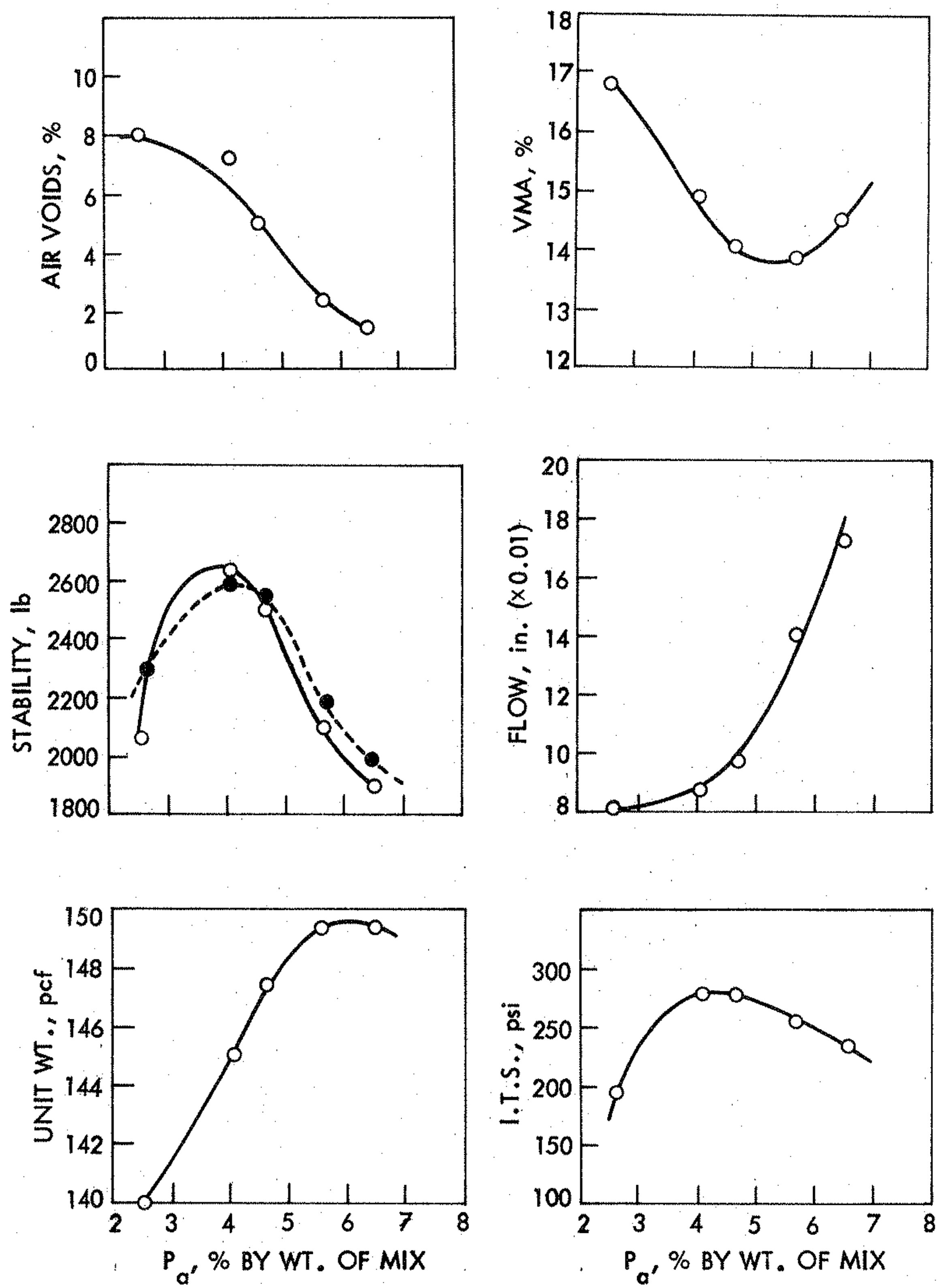

Fig. 7a. Typical Marshall property curves, D006-010 (C-I).

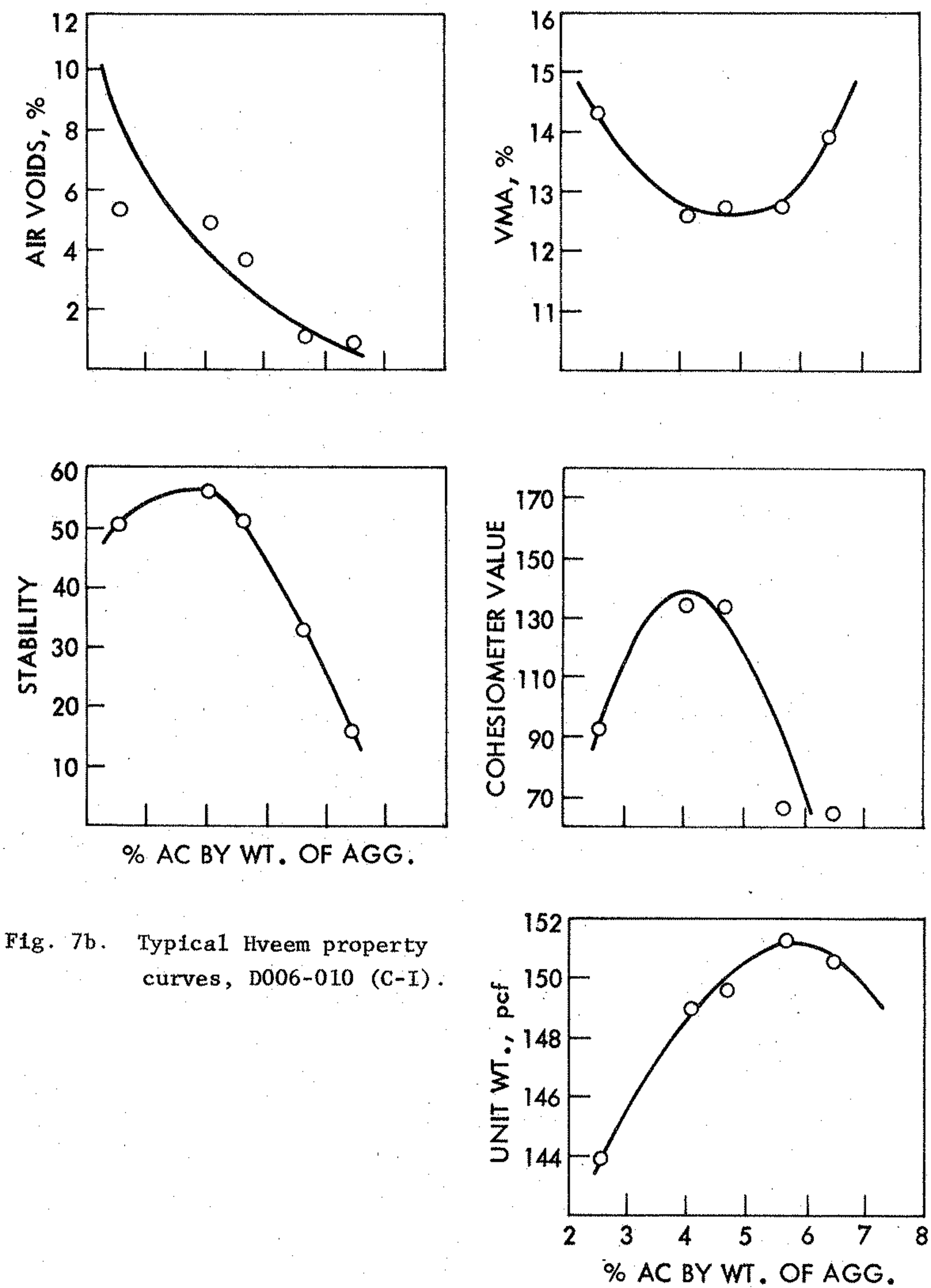

Fig. 7b. Typical Hveem property curves, D006-010 (C-I).

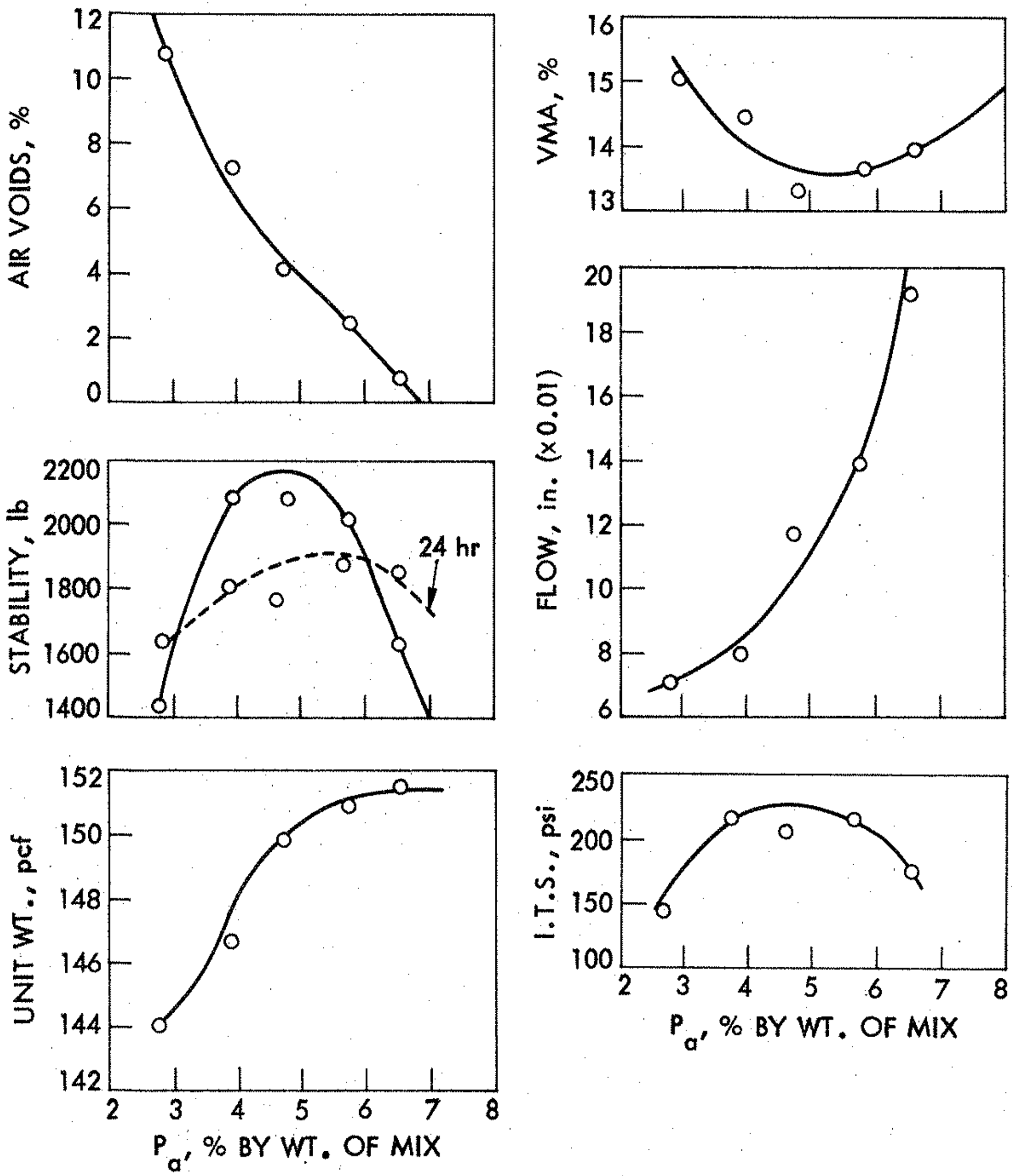

Fig. 8a. Typical Marshall property curves, F031-035 (A-100).

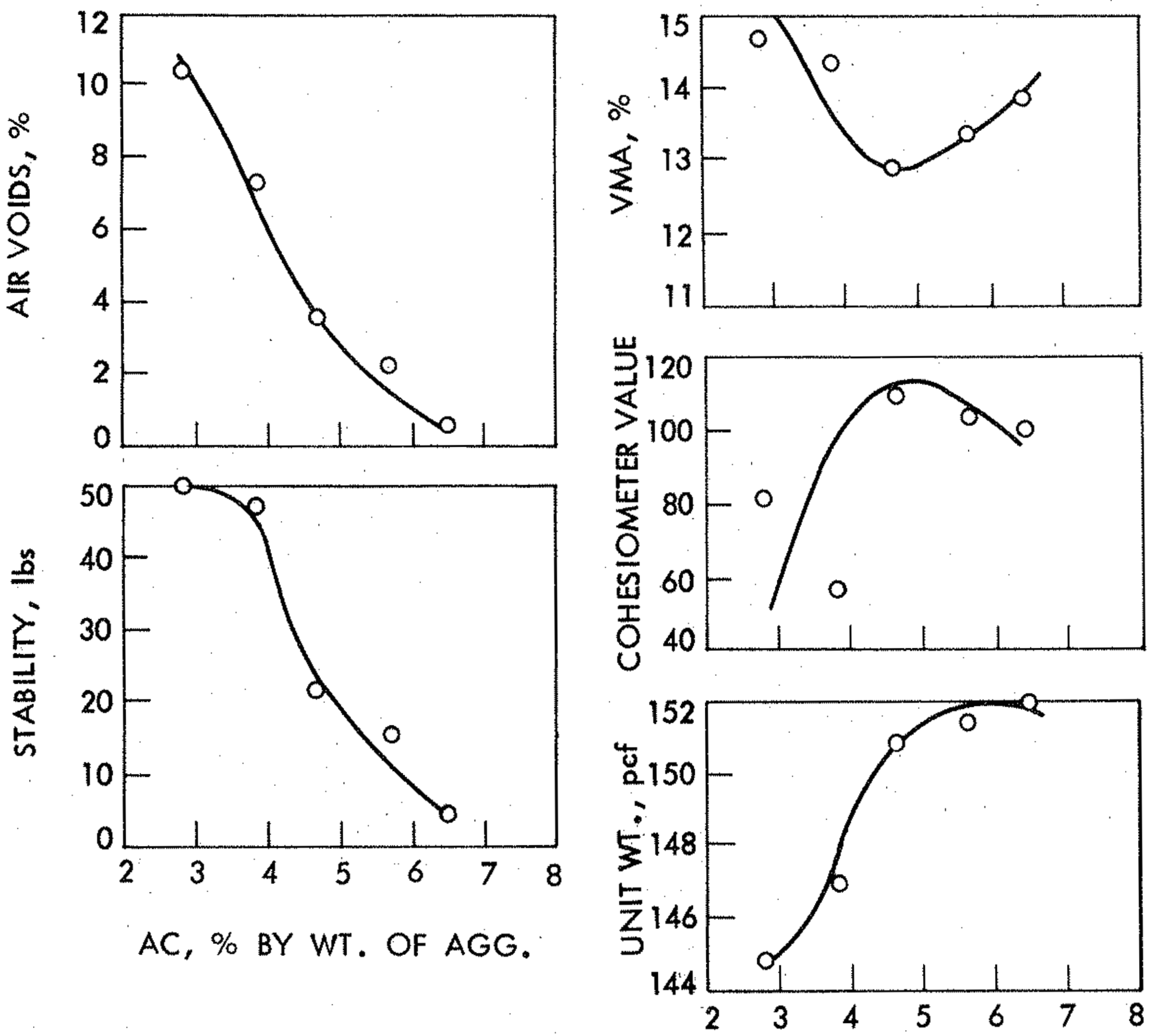

Fig. 8b. Typical Hveem property curves, F031-035 (A-100).

IV. RESULTS AND DISCUSSION

The results of analysis and discussion concerning compaction correlation and effects of interaction of mix variables (Series A) will be presented in Volume II of this report. In the following sections only results concerning Series B to F will be presented and discussed.

Marshall Properties

The results of tests on Marshall specimens are calculated and tabulated in the Appendix G-1 to J-1. The preperty tables include batch and specimen numbers, percentage of asphalt by weight of aggregate and by weight of mix, bulk specific gravity, Rice specific gravity, percent VMA, percentage air voids, unit weight, adjusted stability, flow, tensile strength and gradation.

Density and Gradation

For many years it has been assumed or believed that well graded or Fuller's curve gradings gave mixtures of highest density for a particular aggregate and a maximum size. An examination of bulk specific gravity (unit weight) data in this study indicates that this may not always be the case.

From the unit weight-asphalt content plots, the maximum densities for each gradation in Series B, C, D, and F were determined. The high and low maximum density gradings within each series for Marshall specimens were identified and listed in Table 12, together with well-graded mixes (I,F, and P). The following information was noted:

Table 12. Maximum Marshall density vs gradation and size.

Series	Size, in.	High Grading	High Unit wt.	I	F	P	Low Grading	Low Unit wt.
B L1 x 94	3/4	A-30H A-8	151.5 151.0	149.8	147.7	149.7	A-P A-30L	149.7 149.5
	1/2	B-30 B-P	152.4 151.6	—	—	151.6	B-100L B-30L	148.1 147.5
	3/8	C-100 C-8L	152.4 151.8	149.3	—	150.0	C-100L C-30	150.2 149.3
C L1 x 65	3/4	A-100 A-8L	151.4 150.8	—	148.3	—	A-8 A-100L	148.2 146.8
	1/2	B-8L	150.0	—	—	149.3	B-B B-100L	148.0 148.0
	3/8	C-8	150.7	—	—	—	C-100L C-30	149.2 148.5
D L2 x 65	3/4	A-8LH A-4L A-30LH	153.2 153.1 152.0	152.5	—	152.4		
	1/2	B-30 B-8	151.5 151.3	—	—	—	B-30L	151.0
	3/8	C-8L	154.2	149.6	—	151.6	C-I	149.6
F G x 91	3/4	A-8L A-P A-4L A-4	154.0 152.9 152.4 152.2	—	—	152.9	NG A-100L	143.5 150.4

1. In general, softer asphalt resulted in higher compacted density.
2. The harder Moscow limestone (L2) resulted in higher compacted density for comparable gradings, sizes, and asphalt consistency.
3. In most series, contrary to popular belief, the well-graded gradings (F) were not among the gradings that gave the highest maximum density; perhaps even more surprising is the fact that some of these so-called "dense gradings" (A-P, A-F, C-I, etc) gave some of the lowest maximum densities.

4. Gradings that consistently yielded mixtures of higher maximum density were: A-4L, A-8L, B-30, and C-8L. Gradings that consistently yielded lower maximum density were: A-100L, B-30L, B-100L, C-I, C-30, and C-100L. It appeared that gaps created by reducing fines from P gradings between No. 4 and No. 8 sieves, between No. 8 and No. 16 for 3/4-in. size (A-4L and A-8L) gap, between No. 30 and No. 50 sieves for 1/2-in. size (B-30) gap, and between No. 8 and No. 16 sieves for 3/8-in. size (C-8L), would increase the compacted density. On the other hand, gaps created by removing fines between No. 100 and No. 200 sieves would decrease the compacted density.
5. Gap-graded mixtures, where gaps were created by increasing fines, e.g., B-30, usually resulted in higher maximum densities than these where gaps were created by removing fines, e.g., B-30L.
6. Finally, it can be stated that gap-graded asphalt mixtures do not necessarily result in lower density, provided that gaps are not created by removing fines (No. 100 to No. 200 sieve fractions). More often than not, the opposite may be true.

Some of these features are shown in Figs. 9a to 9d for Marshall mixes in Series B.

The same general statements can be made for Hveem specimens except that the latter usually had higher densities (See Fig. 10).

Stability and Gradation

When the maximum Marshall stability (determined from stability vs percentage of asphalt plots) of various gradings were compared within

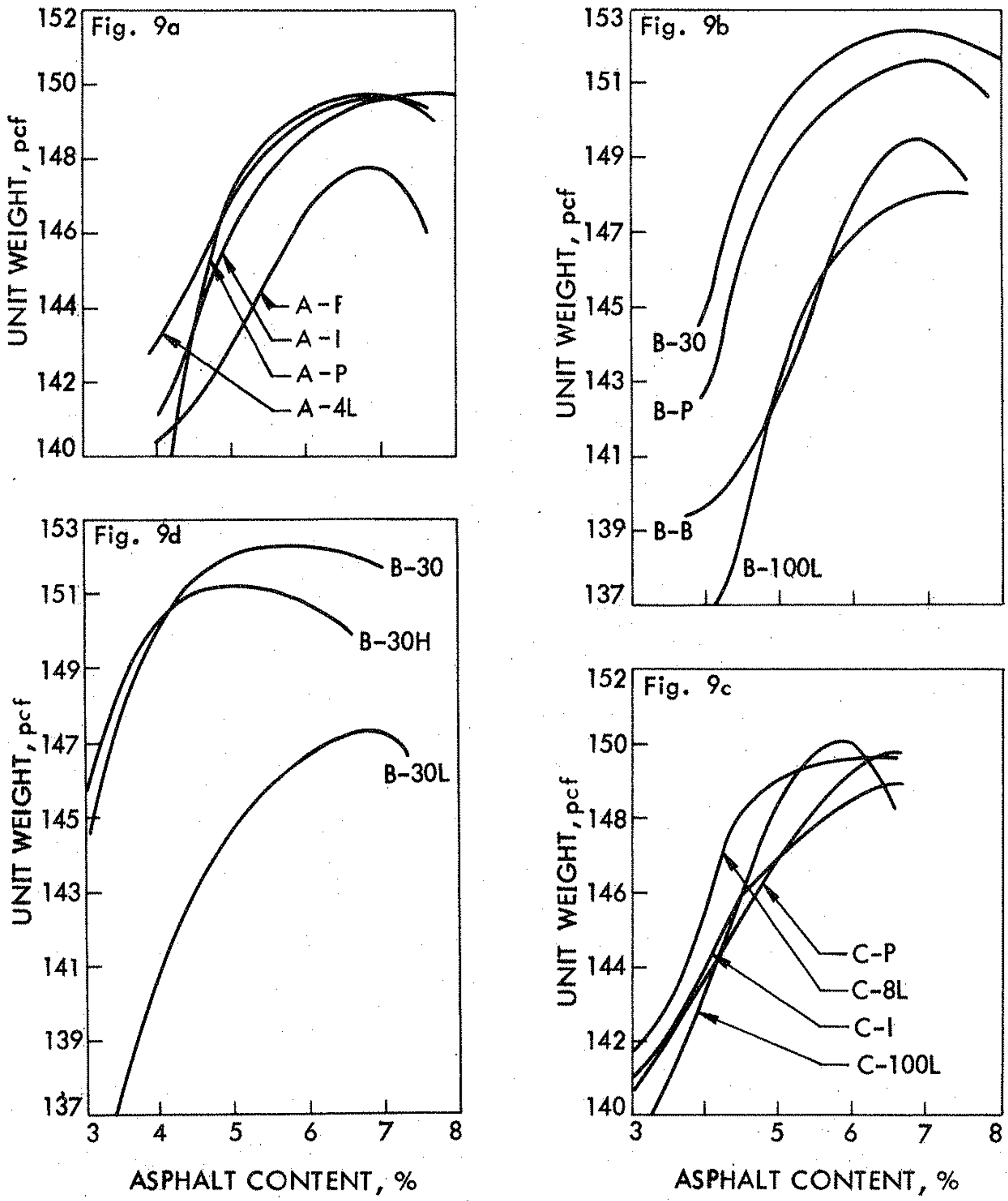

Fig. 9a. High and low Marshall unit weights, Series B, 3/4 in.
Fig. 9b. High and low Marshall unit weights, Series B, 1/2 in.
Fig. 9c. High and low Marshall unit weights, Series B, 3/8 in.
Fig. 9d. Comparison of Marshall unit weights among B-30, B-30H, and B-30L, Series B.

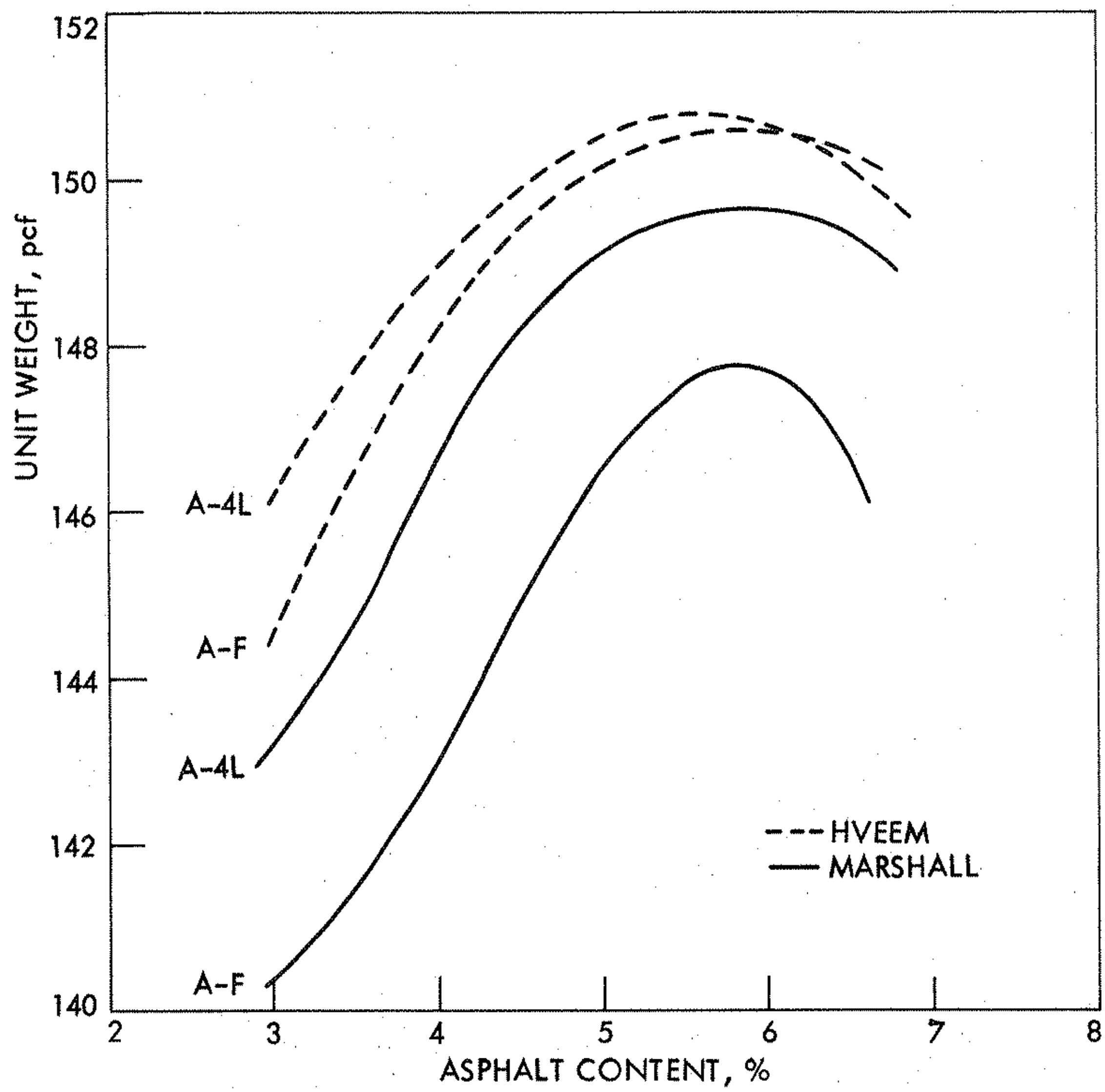

Fig. 10. Differences between Marshall and Hveem unit weight.

each series and between series B, C, D, and F. The following were observed:

Series B (L_1 x 94 pen.)

1. The maximum stability for 3/4-in. size mixes ranged from 2290 lb (A-100) to 4480 lb (A-30); the maximum stability for 1/2-in.

mixes ranged from 3280 lb (B-100L) to 4640 lb (B-30); those for 3/8-in. mixes ranged from 2900 lb (C-100L) to 4640 lb (C-100). It is significant that all mixes, gap or well graded, yielded the maximum stability, far exceeding the minimum of 750 lb required for heavy traffic.

2. Four of the fourteen gap-graded 3/4-in. mixes, 3 of the 7 gap-graded 1/2-in. mixes, and 2 of the 6 gap-graded 3/8-in. mixes had higher maximum stabilities than their corresponding well-graded counterparts (I, F, or P). Four 3/4-in. gap-graded mixes had maximum stabilities lower than those of their well-graded counterparts.
3. The best gaps for high stability mixes appeared to be different for different maximum size gradings. For the particular combination of Ferguson limestone and 94-pen. asphalt cement, the "winners" were A-30, A-30H, A-8L, A-8, A-8H, B-30, B-8L, B-B, C-100, C-8L, and C-8.
4. The undesirable gaps with respect to stability were No. 100 and No. 200 sieves for 1/2-in. and 3/4-in. mixes, and No. 30 to No. 50 sieves for 3/8-in. mixes.
5. Whether the gaps were created by adding fines or removing fines made little differences on stability, except for the 3/8-in. mixes in connection with a No. 100 to No. 200 sieve gap, in which case the mix with the gap between No. 100 and No. 200 created by adding fines increased stability; the mix with the same gap but created by removing fines reduced the stability.

Series C (L_1 x 65 pen.) and D (L_2 x 65 pen.)

1. The maximum stability for Series C ranged from 4050 lb (B-B) and 3590 lb (B-P) to 1950 lb (C-30L); those for Series D ranged from 3130 lb (A-I) to 3030 lb (A-P) to 1960 lb (B-30L). Again the maximum stabilities of all gradings far exceeded the minimum requirement of 750 lb.
2. The best gap gradings for stability in Series C were: A-4, A-100, A-30H, A-8, B-B, and C-100L; the poor gap gradings were: A-8L, A-100L, B-100, B-100L, and C-30L.
3. For the harder limestone Series D, the conventional well-graded mixes (A-I, A-P, C-P and C-I) out-ranked the gap-graded mixes in respective sizes in regard to the maximum stability. The best gradings for maximum stability were: A-I, A-P, A-30, A-8H, A-8LH, B-30, C-P, and C-100.

Series F (G x 91 pen.)

1. The ranges of the maximum stability for crushed gravel ran from 1770 lb (A-100L) to 2620 lb (A-P), all higher than the maximum stability for natural gravel of natural grading (1180 lb), but all lower than the corresponding mixes made with crushed limestone.
2. The high stability gradings in this series were: A-P, A-8L, A-30L, and A-30. The low stability gradings were: A-100L and natural gravel (NG).

The best gradings with respect to the maximum stability among all four series were: B-30 (4640 lb), A-30 (4480 lb), C-100 (4450 lb), A-30H (4140 lb), A-8L (4130 lb), and C-8L (4060 lb), all in Series B. The lowest stability gradings among crushed limestone mixes (B, C, D) were: A-30LH, A-30L, A-4L, and B-30L in Series D, C-30L, A-8L, and A-100L in Series C, and A-100 in Series B.

Figures 11a to 11c show some of the high and low Marshall stability gradings in Series B, in comparison with well-graded mixes.

VMA and Grading

Minimum VMA requirements are recommended by the Asphalt Institute's Marshall method. The purpose of minimum VMA requirements is to ensure that there is sufficient intergranular void space for both enough asphalt for durability and enough air voids to prevent flushing.

The effects of gap-grading for Series B mixtures are shown in Figs. 12a to 12d. As has been expected and considered by many as one of the disadvantages of well-graded aggregates, the well-graded mixtures produced mixtures of low VMA. However, data from Series B indicated that gapping the grading may and may not increase the VMA values. While all gap-graded mixtures gave VMA values higher than that of B-P, gap-graded A-100, A-8, and C-100 mixtures had VMA values lower than corresponding well-graded mixtures. Further, the effects of the location of the gap on VMA were also different for different maximum sizes. The only gap that seemed consistently increased the VMA was No. 30 to No. 50 sieves. Nor was there simple relationship between method of gapping (above or below the P-curve) and VMA values, this was illustrated in Fig. 12d.

Overall Marshall Properties

To make comparisons among various gradings of some 400 mixes tested in this study, based on their mechanical properties, and to determine

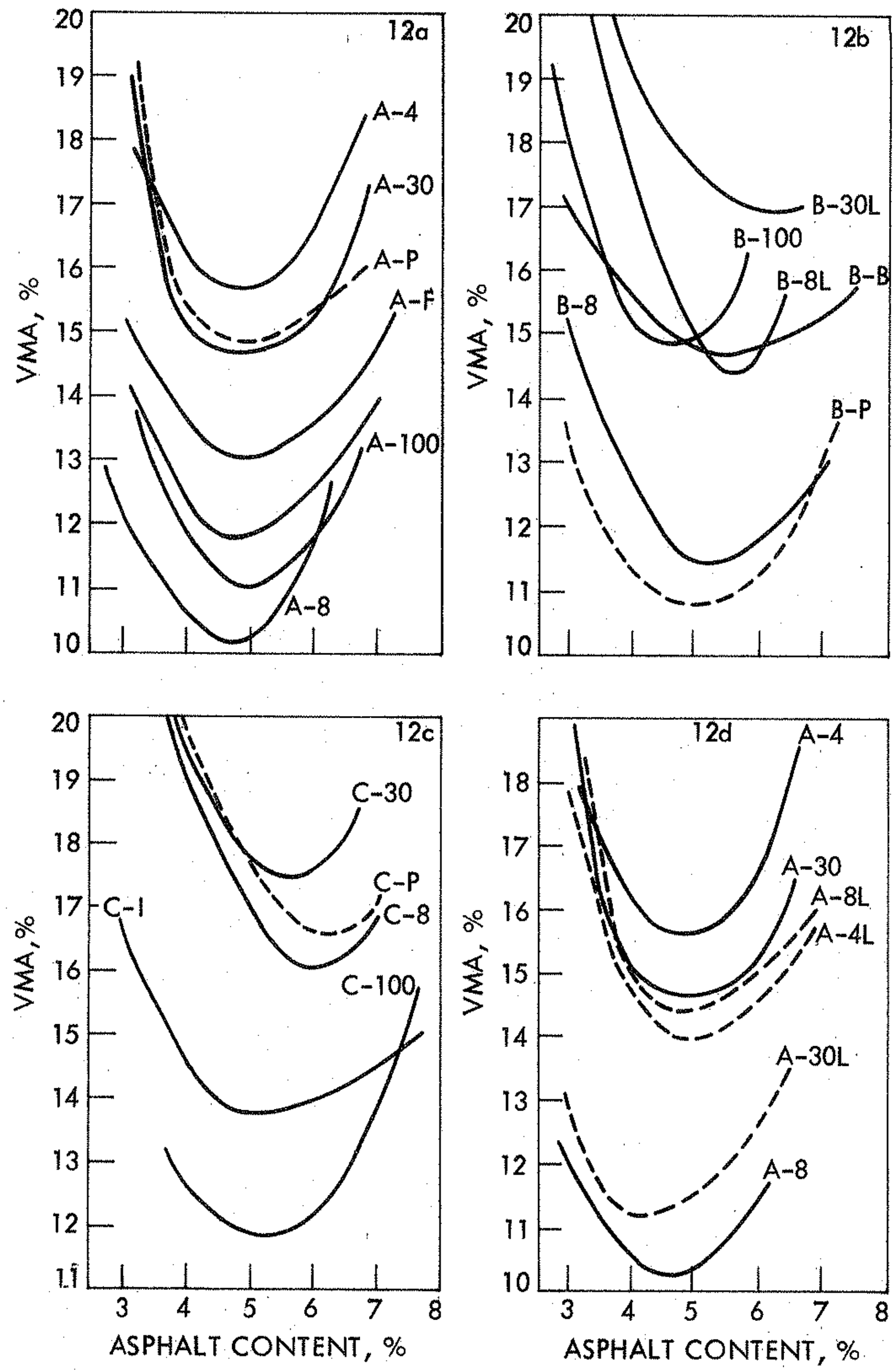

Fig. 12. Effects of gap grading on VMA for Series B mixtures.

the best gap-gradings (or to "pick the winner"), systems and criteria must be developed so mixes can be compared and ranked based on their Marshall or Hveem properties. No such systems are available and, apparently, to our knowledge, no serious attempt on this has ever been made — even though there are practical reasons for such systems and approaches in mixture design and selection.

Although many studies and reports have been published on bituminous concrete mixture design, there seems to be no consensus on the relative importance or significance of the various mixture properties. Nor is there precise agreement on the interpretation of the criteria used in the conventional mixture design methods, especially in light of recent findings on fatigue, stiffness or modulus, and other material properties to be considered in the rational structural design of pavements.

The problem is further complicated by the fact that:

- There is question whether Marshall or Hveem methods and test properties can be used to evaluate or rate asphalt paving mixture quality. There are those who hold the view that "the only thing the Marshall procedures can be used for is to establish optimum asphalt content"[29].
- The use of standard Marshall and Hveem methods have been limited to the dense-graded mixtures. There is a question as to whether the same criteria can be used for gap-graded mixtures.

Even though there are limitations of the Marshall and Hveem methods and though they do not directly measure the basic shear strength parameters (φ and c) of the mixture and are somewhat empirical in nature, it is believed that they can be used to evaluate and compare different paving mixtures with respect to mechanical stability and durability or overall mixture quality based on the following reasonings:

- Both the Marshall and Hveem methods have been successfully used by many highway departments and engineers to design paving mixtures for many years;

- Both methods have been backed by extensive correlations with field mixture performance;

- There have been reasonable correlations between these stability measures and shear strength parameters (internal friction angle φ and cohesion c)[30,31].

Consequently, a system of ranking different mixes by conventional design methods and parameters was developed. Nine different approaches or sets of criteria were adopted for ranking Marshall specimens; five different sets of criteria were used to rank the Hveem specimens. It is anticipated that the final test of how good are these various sets of criteria in evaluating and predicting performance of asphalt mixtures will be a field test; such a program will be proposed in conjunction with the next phase of this study. In any case, one of the important innovations in this investigation is the expanding of the usefulness of the conventional mix design procedures, beyond merely selection of the optimum asphalt content, to the evaluation of mix properties.

<u>Ranking Mixtures by Marshall Procedure</u>

Nine sets of criteria were used, four by standard stability, two by use of 24-hr. immersion stability, two by indirect tensile strength and one by quality index models developed from questionnaires. Though not used in this investigation, potentially possible approaches may include other mixture parameters derived from combined considerations of Marshall stability and flow values, such as bearing capacity, proposed by Metcalf[32], and stability-flow ratio or modulus, proposed by Please[33].

I. By Stability

A. Standard method[28] — stability at optimum asphalt content.

1. Determine the optimum asphalt content p_o from asphalt content-property curves.

   a. Determine asphalt content at maximum stability, P_s.

   b. Determine asphalt content at maximum density or unit weight, P_d.

   c. Determine asphalt content at 4% (or nearest but within 3-6%) air voids, P_a.

   d. Optimum asphalt content $p_o = 1/3\ (P_s + P_d + P_a)$.

2. Check the relevant properties at the optimum asphalt content against the following criteria:

   a. Stability at p_o: $Sp_o \geq 750$.

   b. Air voids at p_o: $3 \leq Ap_o \leq 6$.

   c. Flow at p_o: $8 \leq Fp_o \leq 16$.

   d. VMA at p_o: $Vp_o \geq 14$ for A gradings

      $Vp_o \geq 15$ for B gradings

      $Vp_o \geq 16$ for C gradings.

3. If properties at p_o meet all the above criteria, rank the mixture by Sp_o.

4. If some of the properties at p_o do not meet the criteria, modify Sp_o by the following factors and then rank by modified $Sp'_o = Sp_o \times R$, where

   R = 0.75 if fails 1 criterion
   R = 0.50 if fails 2 criteria
   R = 0.25 if fails 3 criteria
   R = 0.00 if fails 4 criteria.

B. Rank by stability at 3% air voids, S_3: determine asphalt content at 3% air voids (may extrapolate). Determine stability corresponding to 3% air voids, S_3. Record S_3 and rank mixtures by S_3.

C. Rank by maximum stability, S_m.

3. Percentage of retained stability (PRS):

$$PRS_3 = \frac{\text{24-hr. stability at 3\% air voids}}{\text{original stability at 3\% air voids}} \times 100$$

4. Record and rank by PRS_3.

B. By percentage of retained stability at an asphalt content of maximum standard stability:

1. Determine maximum standard stability S_m (from standard stability vs asphalt content curve).

2. Determine immersion stability at an asphalt content corresponding to maximum standard stability S_r (from immersion stability vs asphalt content curve):

$$PRS_m = \frac{S_r}{S_m} \times 100$$

3. Record and rank by PRS_m.

III. By Indirect Tensile Strength (T)

A. Determine the maximum tensile strength T_{max} from tensile strength vs asphalt content plot. Record and rank by T_m.

B. Determine the tensile strength T_3 at 3% air voids (may be extrapolated) and rank according to T_3.

Rankings of Marshall mixes by the above-discussed criteria are tabulated in Tables 13a, 13b, 13c, and 13d. Ranks of gradings are given in Tables 14a, 14b, 14c, and 14d.

Series B

Based on Asphalt Institute criteria (1-A), many of the Marshall mixes, including well-graded mixes I, and F gradings, did not meet all the requirements, mainly due to low VMA or air voids that were outside the 3-6% range. Many of these mixes were marginal: one percent off the required range of air voids and lower limits of VMA. Including those mixes that narrowly missed one of the voids criteria, 22 out of 33

Table 13a. Mix rankings by Marshall methods — Series B.

Batch No.	Gradation	Criteria 1-A				1-B		1-C		1-D			2-A		2B		3-A		3-B		
		P_o	SP_o	SP_o'	Rank	S_3	Rank	S_m	Rank	S_w	Rank	I − E	PRS_3	Rank	PRS_m	Rank	T_m	Rank	T_3	Rank	4
B001-005	B-8	5.6	2950	2213	20 (24)[a]	2550	28(36)	3390	19(20)	2576	17(24)	20.8	90	19 (24)	102	5 (7)	295	9 (13)	210	17 (27)	17.0
B006-010	A-30H	4.1	3840	1920	24 (32)	4050	3 (3)	4140	4 (4)	3064	9(11)	9.8	88	20 (26)	86	16[b] (23)	340	3[b] (6)	280	10[b] (13)	11.4
B011-015	B-P	4.6	3400	2550	14[b] (17)	3250	9(12)	3800	10(10)	2949	11(13)	11.0	94	15 (20)	93	10 (16)	310	7[b] (10)	280	10[b] (13)	11.1
B016-020	C-100	4.3	3600	2700	11 (13)	3150	12(15)	4450	3 (3)	761	29(67)	13.8	99	10[b] (15)	87	15[b] (22)	280	12[b] (16)	265	12[b] (16)	13.5
B021-025	C-100L	4.5	2820	2115	22 (28)	2680	26(31)	2900	31(35)	580	33(72)	27.8	98	11 (16)	84	18[b] (24)	285	11[b] (15)	280	10[b] (13)	20.4
B026-030	B-30	4.5	4450	2225	19 (23)	4600	1 (1)	4640	1 (1)	3248	7 (8)	6.8	93	16[b] (21)	92	11[b] (17)	255	17 (21)	240	15 (21)	11.1
B031-035	A-30L	4.4	2910	2183	21 (25)	2660	27(32)	3070	28(31)	2392	18(25)	23.3	91	18 (23)	92	11[b] (17)	270	14 (18)	260	13[b] (17)	19.0
B036-040	A-8	3.9	3730	1865	25 (36)	3800	4 (5)	3830	9 (9)	3256	6 (7)	11.0	96	13[b] (18)	96	7[b] (13)	325	4[b] (7)	270	11[b] (15)	10.3
B041-045	A-I	4.8	3500	1750	26 (41)	3570	5 (6)	3740	11(11)	1496	23(54)	16.3	93	16[b] (21)	85	17 (29)	285	11[b] (15)	285	9[b] (12)	14.8
B046-050	A-30LH	5.4	2900[c]	1450	31 (56)	3080	15(18)	3260	24(25)	2934	12(14)	20.5	93	16[b] (21)	92	11[b] (12)	300	8[b] (12)	290	8[b] (11)	16.0
B051-055	A-F	4.3	3010[c]	2258	18 (22)	2770	25(30)	3440	17(18)	688	31(69)	22.5	104	7 (10)	97	6[b] (12)	265	15[b] (19)	265	12[b] (16)	16.8
B056-060	C-I	5.5	3030[c]	2273	17 (21)	2820	23(27)	3430	18(19)	1290	26(59)	20.8	92	17[b] (22)	92	11[b] (17)	310	7[b] (10)	310	6 (8)	15.9
B061-065	A-8LH	4.5	3080	1540	30 (53)	3130	13(16)	3150	26(28)	2678	15(19)	21.0	93	16[b] (21)	89	13[b] (20)	260	16 (20)	235	16 (22)	18.5
B066-070	A-30	5.1	4250[c]	3188	3 (4)	4480	2 (2)	4480	2 (2)	4480	1 (1)	2.0	92	17[b] (22)	92	11[b] (17)	320	5[b] (8)	315	5[b] (7)	6.1
B071-075	A-4L	4.7	3240[c]	2430	15[b] (19)[b]	3280	8(10)	3300	22(23)	3300	4 (5)	12.3	95	14 (19)	94	9 (15)	265	15[b] (19)	260	13[b] (17)	12.9
B076-080	A-4LH	5.1	3150[c]	1575	29 (52)	3160	11(14)	3160	25(27)	2854	13(15)	19.5	96	13[b] (18)	96	7[b] (13)	340	3[b] (6)	340	3[b] (5)	13.4
B081-085	A-8H	4.7	3240		1 (2)	3100	14(17)	3650	13(13)	730	30(68)	14.5	97	12 (17)	84	18[b] (24)	370	1 (3)	370	1 (2)	11.3
B086-090	B-8L	5.0	3150		6 (7)	2930	20(25)	3860	7 (7)	1544	22(52)	13.8	99	10[b] (15)	83	19 (25)	320	5[b] (8)	320	4[b] (6)	11.6
B091-095	B-30L	5.7	3220		2[b] (3)[b]	3000	18(22)	3500	15(16)	2800	14(17)	12.3	83	21 (28)	86	16[b] (23)	325	4[b] (7)	315	5[b] (7)	11.9
B096-100	C-P	5.2	3220		2[b] (3)[b]	2800	24(26)	3720	12(12)	2976	10(12)	12.0	96	13[b] (18)	86	16[b] (23)	320	5[b] (8)	290	8[b] (11)	11.3
B101-105	B-B	5.9	3810[c]	2858	10 (12)	3230	10(13)	3850	8 (8)	3292	5 (6)	8.8	117	2 (2)	106	3 (4)	280	12[b] (16)	255	14 (18)	8.1
B106-110	A-8L	4.2	3590[c]	2693	12 (14)	3070	16(19)	4130	5 (5)	1652	20(50)	13.3	78	22 (29)	90	12 (19)	320	5[b] (8)	300	7 (10)	12.6
B111-115	B-100L	5.1	2650		13 (15)	2400	30(41)	3280	23(24)	1312	25(58)	22.8	110	4 (4)	78	21 (28)	340	3 (6)	340	3[b] (5)	15.3
B116-120	C-8L	4.7	3180		4 (5)	2920	22(26)	4060	6 (6)	1624	21(51)	13.3	118	1 (1)	79	20 (27)	320	5[b] (8)	320	4[b] (6)	10.3
B121-125	A-4H	4.4	3030		7 (9)	2930	21(25)	3350	20(21)	1340	24(56)	18.0	108	5 (6)	87	15[b] (22)	280	12[b] (16)	280	10[b] (13)	14.6
B126-130	B-100	4.9	3420[c]	2565	14[b] (17)[b]	3420	6 (8)	3460	16(17)	3460	2 (3)	9.5	98	11[b] (16)	96	7[b] (13)	315	6 (9)	280	10[b] (13)	9.5
B131-135	C-8	5.6	3230[c]	2423	16 (21)	3330	7 (9)	3620	14(14)	3439	3 (4)	9.8	105	6 (9)	107	1 (3)	300	8[b] (12)	290	8[b] (11)	6.0

Table 13a. Series B, continued.

Batch No.	Grad-ation	1-A P_o	1-A SP_o	1-A SP_o'	1-A Rank	1-B S_3	1-B Rank	1-C S_m	1-C Rank	1-D S_w	1-D Rank	I − E	2-A PRS_3	2-A Rank	2-B PRS_m	2-B Rank	3-A T_m	3-A Rank	3-B T_3	3-B Rank	4
B136-140	A-100L	5.0	2500		15[b] (19)	2500	29(39)	2900	31(35)	2320	19(27)	21.0	102	8 (12)	97	6[b] (12)	290	10[b] (14)	285	9[b] (12)	15.1
B141-145	A-4	4.6	2920		9 (11)	2820	23(27)	3060	29(32)	1224	27(60)	22.0	93	16[b] (21)	104	4 (6)	290	10[b] (14)	280	10[b] (13)	16.0
B146-150	C-30L	5.2	2650[c]	1988	23 (29)	2210	31(47)	2950	30(34)	590	32(71)	28.8	96	13[b] (18)	95	8 (14)	275	13 (17)	270	11[b] (15)	20.4
B151-155	A-P	4.8	3000		8 (10)	2950	19(26)	3100	27(30)	3100	8(10)	15.5	100	9[b] (14)	97	6[b] (12)	360	2 (4)	360	2 (3)	10.6
B156-160	C-30	5.9	3160		5 (6)	3060	17(20)	3310	21(22)	2648	16(20)	14.8	113	3 (3)	106	2 (4)	325	4[b] (7)	315	5[b] (7)	8.9
B161-165	A-100	4.7	2020	1010	32 (66)	1480	32(65)	2290	32(50)	916	28(63)	31.0	100	9[b] (14)	89	13[b] (20)	170	18 (29)	160	18 (29)	23.3

[a] Numbers in parentheses indicate overall ranking in the four series. [b] More than one mix (grading) with same ranking. [c] Marginal.

Table 13b. Mix rankings by Marshall method — Series C.

Batch No.	Grad-ation	1-A P_o	1-A SP_o	1-A SP_o'	1-A Rank	1-B S_3	1-B Rank	1-C S_m	1-C Rank	1-D S_w	1-D Rank	I − E	2-A PRS_3	2-A Rank	2-B PRS_m	2-B Rank	3-A T_m	3-A Rank	3-B T_3	3-B Rank	4
C01-05	C-100L	5.8	3280	2460	4(18)[a]	3270	4(11)	3300	4 (23)	2805	4(16)	4.0	105	1 (9)	106	2 (4)	390	1 (1)	380	1 (1)	2.6
C06-10	B-P	5.2	3430	2572	3(16)	3330	3 (9)	3585	2 (15)	3575	1 (2)	2.3	98	6[b] (16)	93	10 (16)	375	2 (2)	350	2 (4)	3.6
C11-15	B-B	6.8	4030		1 (1)	3850	1 (4)	4060	1 (6)	3248	2 (8)	1.3	100	5[b] (14)	100	6[b] (9)	345	3 (5)	300	5[b] (10)	3.0
C16-20	A-4	5.4	3490	1745	13(42)	3500	2 (7)	3500	3 (16)	3150	3 (9)	5.5	101	4 (13)	101	5 (8)	305	7[b] (11)	300	5[b] (10)	5.3
C21-25	A-100	4.6	3060		2 (8)	2980	6(23)	3200	5[b] (26)	2688	5(18)	9.5	94	7[b] (20)	97	7 (12)	325	4[b] (7)	305	4 (9)	4.8
C26-30	A-4LH	4.8	2540	1905	9(33)	2050	15(58)	2620	12 (43)	1780	13(47)	12.3	100	5[b] (14)	95	9 (14)	310	6[b] (10)	265	10 (16)	9.9
C31-35	A-8L	4.2	2050	512	17(72)	2060	14(57)	2080	15 (57)	1330	15(57)	15.3	93	8 (21)	100	6[b] (9)	270	10 (18)	270	9[b] (15)	11.8
C36-40	B-100L	4.9	2300	1725	14(43)	2150	13(51)	2430	13 (44)	1850	12(44)	13.0	85	9 (27)	87	12 (22)	280	9[b] (16)	280	7 (13)	11.1
C41-45	A-30H	5.0	2900	2180	6(26)	2650	7(33)	3200	5[b] (26)	2595	7(23)	6.3	100	5[b] (14)	109	1 (1)	320	5 (8)	315	3 (7)	4.9
C46-50	A-8	4.9	2860	2140	7(27)	2580	9(35)	3100	7 (30)	2226	8(30)	7.8	94	7[b] (20)	96	8 (13)	310	6[b] (10)	275	8[b] (14)	7.5
C51-55	B-100	4.6	2410	1805	12(39)	1880	17(61)	2840	9 (36)	578	17(73)	13.8	98	6[b] (16)	76	14 (30)	285	8 (15)	245	13 (20)	12.0
C56-60	C-30L	5.8	1910	1430	16(57)	1920	16(60)	1950	16 (60)	1665	14(49)	15.5	103	3[b] (11)	104	4 (6)	280	9[b] (16)	270	9[b] (15)	10.9
C61-65	C-8	5.3	2630	1975	8(30)	2630	8(34)	2730	10 (40)	2185	9(31)	8.8	103	3[b] (11)	100	6[b] (9)	305	7[b] (11)	275	8[b] (14)	7.4
C66-70	A-F	4.5	2500	1875	11(35)	2420	11(42)	2690	11 (41)	2040	11(38)	11.0	104	2 (10)	105	3 (5)	255	11 (21)	255	12 (18)	9.0
C71-75	B-8L	5.0	2540	1900	10(34)	2540	10(37)	2900	8 (35)	580	16(72)	11.0	103	3[b] (11)	91	11 (18)	325	4[b] (7)	300	5[b] (10)	8.4
C76-80	A-100L	5.6	2280	1710	15(44)	2280	12(46)	2310	14 (49)	2075	10(36)	12.8	83	10 (28)	84	13 (24)	280	9[b] (16)	260	11 (17)	11.8
C81-85	C-30	5.6	3040	2280	5(20)	3010	5(21)	3160	6 (27)	2640	6(21)	5.5	103	3[b] (11)	100	6[b] (9)	310	6[b] (10)	290	6 (11)	6.6

[a] Numbers in parentheses indicate overall ranking in the four series. [b] More than one mix (grading) with same ranking.

D. Rank by weighted stability method: first approximation.

$$S_w = S_m \cdot R_a \cdot R_f \cdot R_v$$

Determine the maximum stability S_m from stability vs asphalt content plot. Determine S_w by applying appropriate factors R_a, R_f, and R_v, where R_a is the air void adjustment factor:

Air voids	R_a
3.0-5.0	1.00
2.0-2.9 or 5.1- 6.0	0.95
1.5-1.9 or 6.1- 9.0	0.80
0.9-1.5 or 9.1-12.0	0.40
0.0-0.8 or 12.1+	0.20;

where R_f is the flow value adjustment factor:

Flow	R_f
8-16	1.00
6-07 or 17-18	0.90
4-05 or 19-22	0.80
2-03 or 23-26	0.70
0-01 or 27+	0.50;

and where R_v is the VMA adjustment factor:

VMA			R_v
Grading			
A	B	C	
14+	15+	16+	1.00
12-13	13-14	14-15	0.90
10-11	11-12	12-13	0.80
08-09	09-10	10-11	0.70
07-	08-	09-	0.50

II. By Percentage of Retained Stability: (24-hr immersion)

A. By percentage of retained stability at 3% air voids:

1. Determine standard stability at 3% air voids.

2. Determine 24-hr. immersion stability at 3% air voids.

Table 13c. Mix rankings by Marshall method — Series D.

Batch No.	Grad-ation	Criteria 1-A P_o	SP_o	SP_o'	Rank	1-B S_3	Rank	1-C S_m	Rank	1-D S_w	Rank	I – E	2-A PRS_3	Rank	2-B PRS_m	Rank	3-A T_m	Rank	3-B T_3	Rank	4
D01-05	A-I	3.9	2600	1950	1[b] (31)[a]	2200	5 (48)	3130	1 (29)	2117	6(34)	3.3	97	8[b] (17)	95	7[b] (14)	280	5[b] (16)	275	5 (14)	4.8
D06-10	C-I	5.0	2380	1785	5 (40)	2080	10[b] (55)	2660	7 (42)	2128	5(33)	6.5	105	4[b] (9)	97	6[b] (12)	280	5[b] (16)	260	6[b] (17)	5.9
D11-15	B-8	4.8	2460	1845	3 (38)	2465	3 (40)	2690	6 (41)	2230	2(28)	3.3	107	2 (7)	95	7[b] (14)	340	1 (6)	340	1 (5)	3.0
D16-20	B-30	4.4	2430	1823	4 (39)	2450	4 (41)	2830	3 (37)	1053	12(61)	5.5	106	3[b] (8)	97	6[b] (12)	300	2 (12)	285	3 (12)	4.5
D21-25	A-30L	3.8	1650	1238	13 (61)	1600	14[b] (64)	2080	13 (57)	1778	10(48)	12.3	106	3[b] (8)	88	8 (21)	260	7[b] (20)	250	8[b] (19)	9.4
D26-30	C-100	4.8	2600	1950	1[b] (31)	2160	6 (50)	2420	8[b] (45)	1936	8(43)	5.8	105	4[b] (9)	87	9 (22)	255	8 (21)	240	9 (21)	6.6
D31-35	A-8LH	3.9	2030	1523	9 (54)	2080	10[b] (55)	2380	10 (47)	1447	11(55)	9.8	102	5 (12)	109	1[b] (1)	290	4[b] (14)	280	4 (13)	6.6
D41-45	C-P	4.9	2510	1883	2 (37)	2530	2 (38)	2810	4 (38)	2136	4(32)	3.0	98	7[b] (16)	100	4 (9)	290	4[b] (14)	290	2[b] (11)	3.6
D46-50	B-30L	4.7	1700	1275	12 (60)	1600	14[b] (64)	1960	15 (59)	784	14(65)	13.5	94	11 (20)	97	6[b] (12)	270	6 (18)	260	6[b] (17)	10.4
D51-55	C-8L	4.0	2260	1695	6 (45)	2130	7 (52)	2390	9 (46)	861	13(64)	8.5	97	8[b] (17)	99	5[b] (10)	280	5[b] (16)	255	7 (18)	7.4
D56-60	A-4H	4.4	2140	1605	8 (50)	2120	8 (53)	2330	11 (48)	1948	7(42)	8.3	95	10 (19)	106	3 (4)	260	7[b] (20)	250	8[b] (19)	7.6
D61-65	A-4L	3.9	1780	1335	10 (57)	1820	13 (63)	2120	12 (56)	7802	15(66)	12.5	105	4[b] (9)	83	10 (25)	260	7[b] (20)	260	6[b] (17)	9.6
D66-70	A-8H	4.2	2170	1628	7 (48)	1930	11 (54)	2420	8[b] (45)	1936	8(43)	8.5	108	1 (6)	108	2 (2)	280	5[b] (16)	250	8[b] (19)	6.1
D71-75	A-30LH	4.5	1820	910	15 (68)	1860	12 (62)	1980	14 (58)	1782	9(46)	12.3	98	7[b] (16)	109	1[b] (1)	280	5[b] (16)	260	6[b] (17)	8.5
D76-80	A-P	3.9	1900	950	14 (67)	2100	9 (54)	3030	2 (33)	2636	1(32)	6.3	96	9 (18)	99	5[b] (10)	295	3 (13)	260	6[b] (17)	6.0
D81-85	A-30	4.3	2620	1310	11 (58)	2780	1 (29)	2785	5 (39)	2228	3(29)	4.5	99	6 (15)	99	5[b] (10)	290	4[b] (14)	290	2[b] (11)	4.4

[a] Numbers in parentheses indicate overall rankings in the four series. [b] More than one mix (grading) with same ranking.

Table 13d. Mix rankings by Marshall method — Series F.

Batch No.	Grad-ation	Criteria 1-A P_o	SP_o	SP_o'	Rank	1-B S_3	Rank	1-C S_m	Rank	1-D S_w	Rank	I – E	2-A PRS_3	Rank	2-B PRS_m	Rank	3-A T_m	Rank	3-B T_3	Rank	4
F01-05	A-4	4.7	2110[c]	1583	3 (51)[a]	2070	7(56)	2160	6 (54)	1847	7(45)	5.8	97	3[b] (17)	92	7 (17)	250	5(22)	240	5 (21)	5.4
F06-10	A-4L	4.4	1980	1485	4[b] (55)	1920	8(60)	2140	7 (55)	1541	9(53)	7.0	109	1[b] (5)	108	2 (2)	315	1 (9)	275	1[b] (14)	4.1
F11-15	A-8	5.2	2180[c]	1090	6 (63)	2190	5(49)	2190	4 (52)	1993	5(40)	5.0	100	2[b] (14)	109	1 (1)	300	2(12)	260	4 (17)	3.5
F16-20	A-8L	4.4	2290	1145	5 (62)	2300	2(45)	2310	2[b] (49)	1975	6(41)	3.8	97	3[b] (17)	97	5[b] (12)	235	7(24)	235	6 (22)	4.5
F21-25	A-30	5.0	2200[c]	1650	2[b] (47)	2200	3(48)	2280	3 (51)	2052	3(37)	2.8	109	1[b] (5)	106	3 (4)	285	4(15)	270	2 (15)	2.6
F26-30	A-30L	5.3	2250[c]	1688	1 (46)	2130	4(52)	2310	2[b] (49)	2102	2(35)	2.3	91	4[b] (23)	97	5[b] (12)	240	6(23)	220	8 (25)	4.0
F31-35	A-100	5.6	2050[c]	1025	8 (65)	2100	6(54)	2170	5 (53)	2018	4(39)	5.8	91	4[b] (23)	87	8 (22)	230	8(25)	225	7 (24)	6.3
F36-40	A-100L	5.2	1650		2[b] (47)	1600	10(64)	1770	9 (61)	673	11(70)	8.0	89	5 (25)	96	6 (13)	225	9(26)	215	9 (26)	7.6
F41-45	NC	6.5	1130	848	9 (70)	1080	11(66)	1180	10 (62)	1009	10(62)	10.0	83	6 (28)	80	9 (26)	220	10(27)	205	10 (28)	9.4
F46-50	B-B	7.5	1980	1485	4[b] (55)	1820	9(63)	1980	8 (58)	1782	8(46)	7.3	–	–	–	–	180	11(28)	120	11 (30)	8.5
F51-55	A-P	5.5	2080[c]	1040	7 (64)	2350	1(44)	2620	1 (43)	2358	1(26)	2.5	100	2[b] (14)	98	4 (11)	290	3(14)	265	3 (16)	2.8

[a] Numbers in parentheses indicate overall rankings in the four series. [b] More than one mix (grading) with same ranking. [c] Marginal.

Table 14a. Rankings of Marshall mixes by gradings — Series B.

Size	1-A	1-B	1-C	1-D	2-A	2-B	3-A	3-B	Ranking
	Criteria								
A(3/4 in.)	A-8H	A-30	A-30	A-30	A-4H	A-4	A-8H	A-8H	1
	A-30	A-30H	A-30H	A-4L	A-F	A-F	A-P	A-P	2
	A-4H	A-8	A-8L	A-8	A-100L	A-P	A-4LH	A-4LH	3
	A-P	A-I	A-8	A-P	A-P	A-100L	A-30H	A-30	4
	A-4	A-4L	A-I	A-30H	A-100	A-8	A-8	A-8L	5
	A-8L	A-4LH	A-8H	A-30LH	A-8H	A-4LH	A-30	A-30LH	6
	A-I	A-8LH	A-F	A-4LH	A-8	A-4L	A-8L	A-I	7
	A-4L	A-8H	A-4H	A-8LH	A-4LH	A-30L	A-30LH	A-100L	8
	A-100L	A-30LH	A-4L	A-30L	A-4L	A-30LH	A-100L	A-30H	9
	A-F	A-8L	A-30L	A-100L	A-I	A-30	A-4	A-4H	10
	A-30L	A-P	A-4H	A-8L	A-30LH	A-8L	A-I	A-4	11
	A-30H	A-4H	A-8LH	A-I	A-8LH	A-8LH	A-4H	A-8	12
	A-8	A-4	A-P	A-4H	A-4	A-100	A-30L	A-F	13
	A-4LH	A-F	A-30L	A-4	A-30	A-4H	A-F	A-30L	14
	A-8LH	A-30L	A-4	A-100	A-30L	A-30H	A-4L	A-4L	15
	A-30LH	A-100L	A-100L	A-8H	A-30H	A-8H	A-8LH	A-8LH	16
	A-100	A-100	A-100	A-F	A-8L	A-I	A-100	A-100	17
B(1/2 in.)	B-30L	B-30	B-30	B-100	B-B	B-B	B-100L	B-100L	1
	B-8L	B-100	B-8L	B-B	B-100L	B-8	B-30L	B-8L	2
	B-B	B-P	B-B	B-30	B-8L	B-100	B-8L	B-30L	3
	B-100L	B-B	B-P	B-P	B-100	B-P	B-100	B-P	4
	B-100	B-30L	B-30L	B-30L	B-P	B-30	B-P	B-100	5
	B-P	B-8L	B-100	B-8	B-30	B-30L	B-8	B-B	6
	B-30	B-8	B-8	B-8L	B-8	B-8L	B-B	B-30	7
	B-8	B-100L	B-100L	B-100L	B-30L	B-100L	B-30	B-8	8
C(3/8 in.)	C-P	C-8	C-100	C-8	C-8L	C-8	C-30	C-8L	1
	C-8L	C-100	C-8L	C-P	C-30	C-30	C-P	C-30	2
	C-30	C-30	C-P	C-30	C-8	C-30L	C-8L	C-I	3
	C-100	C-8L	C-8	C-8L	C-100	C-I	C-I	C-P	4
	C-8	C-I	C-I	C-I	C-100L	C-P	C-8	C-8	5
	C-I	C-P	C-30	C-100	C-P	C-100	C-100L	C-100L	6
	C-100L	C-100L	C-30L	C-30L	C-30L	C-100L	C-100	C-30L	7
	C-30L	C-30L	C-100L	C-100L	C-I	C-8L	C-30L	C-100	8

Table 14b. Rankings of Marshall mixes by gradings — Series C.

Size	Criteria 1-A	1-B	1-C	1-D	2-A	2-B	3-A	3-B	Ranking
A(3/4 in.)	A-100	A-4	A-4	A-4	A-F	A-30H	A-100	A-30H	1
	A-30H	A-100	A-100	A-100	A-4	A-F	A-30H	A-100	2
	A-8	A-30H	A-30H	A-30H	A-100	A-4	A-4LH	A-4	3
	A-4LH	A-8	A-8	A-8	A-4LH	A-8L	A-8	A-8	4
	A-F	A-F	A-F	A-100L	A-30H	A-100	A-4	A-8L	5
	A-4	A-100L	A-4LH	A-F	A-8	A-8	A-100L	A-4LH	6
	A-100L	A-8L	A-100L	A-4LH	A-8L	A-4LH	A-8L	A-100L	7
	A-8L	A-4LH	A-8L	A-8L	A-100L	A-100L	A-F	A-F	8
B(1/2 in.)	B-B	B-B	B-B	B-P	B-8L	B-B	B-P	B-P	1
	B-P	B-P	B-P	B-B	B-B	B-P	B-B	B-B	2
	B-8L	B-8L	B-8L	B-100L	B-P	B-8L	B-8L	B-8L	3
	B-100	B-100L	B-100	B-8L	B-100	B-100L	B-100	B-100L	4
	B-100L	B-100	B-100L	B-100	B-100L	B-100	B-100L	B-100	5
C(3/8 in.)	C-100L	C-100L	C-100L	C-100L	C-100L	C-100L	C-100L	C-100L	1
	C-30	C-30	C-30	C-30	C-30	C-30L	C-30	C-30	2
	C-8	C-8	C-8	C-8	C-8	C-8	C-8	C-8	3
	C-30L	C-30L	C-30L	C-30L	C-30L	C-30L	C-30L	C-30L	4

gradings (67%) in this series could be considered acceptable mixes. This figure is considered significant. It means that many gap-graded aggregates can be successfully used, even based on current design criteria.

Rankings based on the Asphalt Institute criteria with equal weight given to all four criteria (1-A) indicate that the best gradings were: A-8H, A-30, A-4H, A-P, B-30L, B-8L, B-B, C-P, C-8L, and C-30 (Table 14a). The optimum asphalt content for gap-graded mixes was usually higher than that for well-graded equivalents, as expected.

Table 14c. Rankings of Marshall mixes by gradings — Series D.

Size	Criteria 1-A	1-B	1-C	1-D	2-A	2-B	3-A	3-B	Ranking
A(3/4 in.)	A-I	A-30	A-I	A-P	A-8H	A-8LH	A-P	A-30	1
	A-8H	A-I	A-P	A-30	A-30L	A-30LH	A-8LH	A-8LH	2
	A-4H	A-4H	A-30	A-I	A-4L	A-8H	A-30	A-I	3
	A-8LH	A-P	A-8H	A-4H	A-8LH	A-4H	A-I	A-4L	4
	A-4L	A-8LH	A-8LH	A-8H	A-30	A-P	A-8H	A-P	5
	A-30	A-8H	A-4H	A-30LH	A-30LH	A-30	A-30LH	A-30LH	6
	A-30L	A-30LH	A-4L	A-30L	A-I	A-I	A-30L	A-30L	7
	A-P	A-4L	A-30L	A-8LH	A-P	A-30L	A-4H	A-4H	8
	A-30LH	A-30L	A-30LH	A-4L	A-4H	A-4L	A-4L	A-8H	9
B(1/2 in.)	B-8	B-8	B-30	B-8	B-8	B-30	B-8	B-8	1
	B-30	B-30	B-8	B-30	B-30	B-30L	B-30	B-30	2
	B-30L	B-30L	B-30L	B-30L	B-30L	B-8	B-30L	B-30L	3
C(3/8 in.)	C-100	C-P	C-P	C-P	C-I	C-P	C-P	C-P	1
	C-P	C-100	C-I	C-I	C-100	C-8L	C-I	C-I	2
	C-I	C-8L	C-100	C-8L	C-P	C-I	C-8L	C-8L	3
	C-8L	C-I	C-8L	C-100	C-8L	C-100	C-100	C-100	4

Rankings of Marshall mixes by stability at 3% air voids (1-B) and by maximum stability (1-C) resulted in a close parallel. The "best" gradings were: A-30, A-30H, A-8 (A-8L), A-I, B-30, B-P, B-B, C-8 (C-8L), and C-100 (Table 14b).

Rankings of Marshall mixes by weighted property adjustment factors (Method 1-D) present a most unique and potentially the most useful and practical approach to mixture evaluation involving different aggregates, sizes, gradings, and type of asphalt. Perhaps even more important, it

Table 14d. Rankings of Marshall mixes by gradings – Series F.

Size	Criteria								Ranking
	1-A	1-B	1-C	1-D	2-A	2-B	3-A	3-B	
A(3/4 in.)	A-30L	A-P	A-P	A-4L	A-4L	A-8	A-4L	A-4L	1
	A-30	A-8L	A-8L	A-30L	A-30	A-4L	A-8	A-30	2
	A-100L	A-30	A-30L	A-30	A-8	A-30	A-P	A-P	3
	A-4	A-30L	A-30	A-100	A-P	A-P	A-30	A-8	4
	A-4L	A-8	A-8	A-8	A-4	A-8L	A-4	A-4	5
	A-8L	A-100	A-100	A-8L	A-8L	A-30L	A-30L	A-8L	6
	A-8	A-4	A-4	A-4	A-30L	A-100L	A-8L	A-100	7
	A-P	A-4L	A-4L	A-4L	A-100	A-4	A-100	A-30L	8
	A-100	A-100L	A-100L	NG	A-100L	A-100	A-100L	A-100L	9
	NG	NG	NG	A-100L	NG	NG	NG	NG	10

could be used for plant and construction quality control or specification writing. The adjustment factors R_a, R_v, and R_f used in this study were subjectively set by the principal investigator and can be modified and/or improved based on further field performance study.

However, the concept and approach is considered the most useful and significant. According to this approach, the "best" gradings in this series were: A-30, A-4L, A-8, A-P, A-30H, B-100, B-B, B-30, B-P, C-8, and C-P (Table 14a). The "poorest" gradings in each size groups were: A-F, B-100L, and C-100L.

When the average rankings of the above four methods were calculated (1-E), the higher ranked gradings were: A-30, B-30, B-B, A-30H, B-100, and C-8.

The second group of ranking criteria were based on the percentage of retained Marshall stability after 24-hr immersion in water at 140 ^{o}F. This parameter has often been used to evaluate the resistance of the compacted mixture to the action of water. For some reason not clear at this time, the percentage of retained stability, both at 3% air void (PRS_3) and at maximum stability (PRS_m) was extremely high. However, for the purpose of ranking the mixes, the consequence is not important, except to note that all mixes met the minimum 75% retained strength requirement specified by the U.S. Corps of Engineers. The rankings of the mixes (gradings) by those two criteria indicated the following "best" gradings: A-4, A-4H, A-F, A-P, A-100L, B-B, B-8, B-100L, C-8, C-8L, and C-30.

Because of the importance of tensile strength in flexible pavement systems and the simplicity and adaptability of the indirect tensile test[34-36], for standard Marshall and Hveem specimens, Marshall specimen No. 6 was tested by indirect tensile test to evaluate the tensile properties of gap-graded asphalt concrete mixtures. The maximum tensile strength (T_m) and tensile strength at 3% air voids (T_3) were determined from plots of tensile strength vs asphalt content. The maximum tensile strength at room temperature of Marshall specimens in this series ranged from a low of 170 psi (A-100) to a high of 370 psi (A-8H). The rankings of gradings by these two criteria are presented in Table 14a for mixes in Series B. The higher ranked mixes (gradings) were: A-8H, A-P, A-4LH, A-30, B-100L, B-8L, B-30L, B-P, C-30, C-8L, C-P, C-I, and C-8.

The rankings of the mixes by the average of the eight methods are given in the last column of Table 13a. The "best" gradings by all criteria were: A-30, A-8, B-B, B-100, C-8, C-30, and C-8L.

Series C (L_1 x 65 pen.)

Based on the Asphalt Institute criteria, only two gradings (B-B and A-100) should be considered acceptable. All the other gradings, except two (A-4 and A-8L), failed only the VMA criterion. The relatively low VMA values for all mixes could be attributed to the low average bulk specific gravity obtained for the aggregate. If this criterion were relaxed all the gradings except A-4 and A-8L would have been considered satisfactory. Rankings of the gradings by equal-weighted stability at optimum asphalt content (Sp'_o) showed the following "best" gradings: A-100, A-30H, B-B, B-P, C-100L, and C-30. The average optimum asphalt contents for the gap-graded mixes was 0.4% higher than the corresponding well-graded mixes (A-F).

Rankings based on stability at 3% air voids (S_3) and the maximum stability (S_m) gave almost identical results. The higher ranked gradings were: B-B, A-4, B-P, C-100L, A-100, C-30, and A-30H.

Rankings based on weighted stability (S_w) obtained from adjustment factors showed surprisingly same results; the "best" gradings were: B-P, B-B, A-4, C-100L, A-100, and C-30.

The average rankings of the mixes by the four Marshall criteria are shown in column 1-E. Again the top ranked gradings were: B-B, B-P, C-100L, A-100, A-4, and C-30. By all five criteria, the Fuller curve grading was ranked 11th out of the 17 gradings in this series.

Comparing the gradings based on the percentage of retained stability at 3% air voids (PRS_3) and at the maximum stabilities (PRS_m) resulted in rankings of a different order; most showed little or no loss of stability after 24-hrs of immersion in water. The higher ranked gradings were: C-100L, A-F, C-30, C-30L, A-4, and A-30H.

The maximum tensile strength of Series C ranged from 255 psi (A-F) to 390 psi (C-100L), higher than those for Series B mixes because of the lower penetration asphalt used. Rankings based on these tensile strength criteria showed that the "best" gradings were: C-100L, B-P, B-B, A-4, A-30H, and B-8L.

The "overall" quality as indicated by the average rankings of the eight approaches (Column 4) gave the following higher order gradings: C-100L, B-B, B-P, A-100, and A-30H, and A-4.

Series D (L_2 x 65 pen.)

Based on the Asphalt Institute criteria, none of the 17 gradings in this series would be considered acceptable. All except three (A-P, A-30, and A-30LH) were due to low (1-3%) VMA values. Considering the inaccurate methods of bulk specific gravity determinations for aggregates and that a deviation of 0.1 in specific gravity of combined aggregate could result in a variation of about 3% in VMA, these mixes could be easily accepted by a more accurate aggregate specific gravity determination. If this were the case, only four gradings (C-P, A-P, A-30, and A-30LH) would not result in satisfactory mixes by current standards.

The rankings of the gradings based on adjusted optimum stability SP'_o were given in Table 14c. The top ranked gradings are: A-I, B-8, B-30, C-100, C-P, and C-I. The higher ranked gradings based on stability at 3% air voids (S_3) were: A-30, A-I, B-8, B-30, and C-P. Those based on the maximum stability (S_m) were: A-I, A-P, A-30, B-30, and C-P.

The weighted maximum stability (S_w) criterion produced the "best" gradings: A-P, A-30, B-8, C-P, and C-I. The average rankings of the first four criteria gave the following gradings higher rankings: C-P, A-I, B-8, A-30, B-30, and C-100. It is interesting to note that, comparing with Series C (L_1 x 65 pen.), the harder Moscow limestone (L_2) scored better for well-graded mixtures of Iowa (I) and the Federal Highway Administration gradings (P) than those for the softer Ferguson aggregate (L_1).

The retained Marshall stabilities of mixes in this series were again exceedingly high. The "winners" based on percentage of retained stability at 3% voids were: A-8H, A-30L, A-4L, B-8, B-30, C-I, and C-100. Those based on the percentage of retained maximum stability were: A-8LH, A-30LH, A-8H, A-4H, and C-P.

The range of the maximum tensile strength at 77 ^oF was from 255 psi (C-100) to 340 psi (B-8). The "winners" based on the two tensile strength criteria were: B-8, B-30, C-P, A-P, and A-30.

The average of eight rankings (considering the "overall" quality of the mixes including Marshall properties, water resistance and tensile strength) made the following gradings, in this series the better gradings: B-8 (3.0), C-P (3.6), A-30 (4.4), B-30 (4.5), A-I (4.8).

Series F (G x 91 pen.)

Only one grading (A-100L) met all the Asphalt Institute criteria by the Marshall procedure. However, six other gradings were marginal, missing void(s) criteria less than one percent. Two other gradings missed the VMA criterion by less than 3%, which could have resulted from a variation of bulk specific gravity of 0.1. Therefore, 9 out of 11 gradings in this series could conceivably be considered acceptable. Rankings of these gradings by adjusted optimum stability Sp_o' indicated that the "best" gradings were: A-30L, A-30, A-100L, and A-4.

Considering only stability of the mixes, either at 3% air voids or the maximum stability would make the following gradings most desirable, we have: A-P, A-8L, A-30, and A-30L.

Based on the weighted stability (S_w) criterion the "best" gradings were: A-P, A-30L, A-30, and A-100. The average stability rankings (1-E), indicated that the top three gradings were: A-30L (2.3), A-P (2.5), and A-30 (2.8). The poorest gradings was the natural graded gravel (NG).

Based on percent retained Marshall stability criteria (2-A and 2-B), the top gradings were: A-4L, A-8, A-30, and A-P.

The maximum tensile strength in this series ranged from 180 psi for natural graded gravel to 315 psi for A-4L. Rankings based on the two tensile strength criteria showed that the desirable gradings were: A-4L, A-8, A-P, and A-30.

The top three gradings when the overall quality of the mixes were considered by averaging the eight rankings were: A-30 (2.6), A-P (2.8), and A-8 (3.5). Note that no matter which criterion is used, the natural gravel produced the poorest mixes.

Ranking of Marshall Mixtures by Marshall Modulus

Since both standard Marshall and Hveem methods have been correlated with the performance, and thus limited to the design of, dense graded mixtures, there may be some question as to the adequacy of the method and criteria when applied to evaluation and design of gap-graded mixes. Obviously correlation studies between results of laboratory tests and the performance of the paving mixes under service conditions should be undertaken to establish new criteria and/or methods.

A recent report by Brier[37] has suggested the use of the Marshall stiffness (S_m, calculated as stability/flow in lb/0.01 in.) for design of gap-graded asphalt mixes. According to correlations between rut depth in a laboratory wheel-tracking test (as well as field rut-depth measurements) with Marshall stiffness, a minimum range of Marshall stiffness of 40 (75 kgf/mm) to 80 (150 kgf/mm) should be required to prevent excessive rutting under traffic.

Based on this criteria, i.e., higher S_m indicates better mix, the S_m at optimum asphalt content for Series B mixes were calculated. The rankings showed that the top ten mixes (gradings) were:

C-100	(400 lb/0.01 in.)
A-30	(386 lb/0.01 in.)
A-8	(373 lb/0.01 in.)
B-30	(342 lb/0.01 in.)
A-I	(318 lb/0.01 in.)
B-B	(318 lb/0.01 in.)
C-100L	(314 lb/0.01 in.)
A-8H	(304 lb/0.01 in.)
C-I	(303 lb/0.01 in.)
A-F	(301 lb/0.01 in.)

All gradings studied met the minimum suggested Marshall stiffness requirement of 80 lb/0.01 in.; the range was from 126 (A-100) to 400 (C-100).

The range of Marshall stiffness for Series C was between 128 (A-8L) and 310 (B-B); the higher ranked gradings based on the Marshall stiffness at optimum asphalt content were: A-4, A-F, B-B, B-P, C-30, and C-100L. The range of Marshall stiffness at the optimum asphalt content for Series D was from 121 for A-30LH to 215 for A-I; that for Series F was from 141 (A-4L) to 198 (A-8). The higher ranked gradings for Series D were A-I, A-30, B-30, B-8, C-100, and C-8L; those for Series F were A-8, A-4, and A-P. The gradings that appeared in the top 30% of each series of mixes in at least two out of the three limestone series (B, C, and D) were: A-30, A-8, A-I, B-30, B-B, C-100, and C-100L.

Rankings of Marshall Mixes Between Series

The top ranked mixes, when all mixes in the four series were compared, are given in Table 15. The salient features of this table are:

Table 15. Top ranked gradings of all mixes — Marshall procedure.

Ranking	Criteria 1-A (SP'_o)	1-C (S_m)	I-D (S_w)	2-A (PRS_3)	3-A (T_m)
1	(C) B-B	(B) B-30	(B) A-30	(B) C-8L	(C) C-100L
2	(B) A-8	(B) A-30	(C) B-P	(B) C-8L	(C) B-P
3	(B) B-30L	(B) C-100	(B) B-100	(B) B-B	(B) A-8H
4	(B) C-P	(B) A-30H	(B) C-8	(B) C-30	(B) A-P
5	(B) A-30	(B) A-8L	(B) A-4L	(F) A-4L	(C) B-B
6	(B) C-8L	(B) C-8L	(B) B-B	(F) A-30	(D) B-8
7	(B) C-30	(B) B-8L	(B) A-8	(D) A-8H	(B) A-30H
8	(B) B-8L	(B) B-B	(B) B-30	(B) A-4H	(B) A-4LH
9	(C) A-100	(B) A-8	(C) A-4	(D) B-8	(B) B-100L
10	(B) A-4H	(B) B-P	(B) A-P	(D) B-30	(B) A-8

- Series B mixes dominated the higher ranked mixes.
- Out of 33 gradings studied, 25 of them appeared in the table more than once, which means that more than 75% of the gradings would be made excellent mixes by certain criteria and appropriate combination of aggregate and asphalt.
- The gradings appearing in the table most frequently were: B-B (5), A-8 (4), A-30 (4), C-8L (4), B-30 (3), B-P (3), A-30H (2), A-4H (2), A-4L (2), A-P (2), A-8H (2), B-8L (2), B-8 (2), and C-30 (2).
- The Federal Highway Administration gradings (A-P, B-P, and C-P) ranked high by all except percentage of retained stability criterion, while the Fuller's curve grading (F) was not among the best mixes by any criterion.
- The Iowa Type A gradings (A-I and C-I) were ranked high by most criteria, especially by Marshall modulus at the optimum asphalt content.

Hveem Properties

The results of tests on Hveem specimens (Specimens 7, 8, and 9) of Series B, C, D, and F are given in Appendixes G-2 to J-2. Presented in the property tables are batch and specimen numbers, percentages of asphalt by weight of aggregate and by weight of mix, bulk specific gravity, Rice (theoretical maximum) specific gravity, air voids, VMA, unit weight, adjusted Hveem stability, and cohesiometer values and gradation.

Density and Gradation

One of the most direct and most important effects of changing particle size distribution or grading is the compacted density. In fact, the most frequent argument for a well-graded or Fuller's curve grading is that it will produce the densest compacted mixture. Therefore, one of the relevant comparisons between gap- and well-graded mixtures is the maximum density or unit weight. Table 16 gives the high and low values of unit weights for Hveem specimens for each series and size. Also tabulated were the unit weights for Iowa Type A (I), Fuller's curve (F), and the FHWA curve (P) gradings.

It can readily be seen that:

- Except for B-P in Series B, the well-graded aggregates did not always produce the highest maximum Hveem density. In certain cases, the continuous-graded Iowa-type-A grading (A-I and C-I in Series D) produced mixtures of lowest maximum unit weights in respective size groups.
- For the same aggregate, size and grading, softed asphalt (Series B) produced a maximum unit weight slightly higher than those made of harder asphalt (Series C).

Table 16. Maximum Hveem density vs grading and size.

Series	Size	High Grading	High Unit wt.	I	F	P	Low Grading	Low Unit wt.
B	3/4 in.	A-30L	152.0	150.6	150.6	150.8	A-8LH	150.2
	1/2 in.	B-P	152.8			152.8	B-30L	149.2
	3/8 in.	C-100	152.8	151.9		150.8	C-30	150.3
C	3/4 in.	A-100	152.4		148.9		A-100L	148.4
	1/2 in.	B-8L	151.0			150.2	B-B	149.5
	3/8 in.	C-8	151.6				C-30	149.6
D	3/4 in.	A-8LH	154.4	152.7		153.5	A-I	152.7
	1/2 in.	B-8	152.4				B-30	152.1
	3/8 in.	C-8L	153.1	151.1		151.6	C-I	151.1
F	3/4 in.	A-8L	153.8			153.5	NG	148.8

- With the same asphalt (Series C vs Series D), harder Moscow aggregates produced somewhat higher unit weight mixtures, with the same grading and maximum particle size.

- No gradings were found to consistently produce the highest maximum density. Only gradings C-30 and natural graded gravel were found to yield the low densities repeatedly.

Attempts were made to identify empirically the "best" gaps for high maximum density and the effects of methods of creating gaps (e.g., 4 vs 4L, 8 vs 8L, etc.) on density, using Series B and F. Neither effort was successful. It appeared that the most critical gaps were No. 30 to No. 50 sieves for all sizes and No. 100 to No. 200 sieves for 3/4- and 3/8-in. maximum size mixes. The No. 30 to No. 50 gap created by increasing fines reduced density for 3/8-in. mixes; however, the same gap created by reducing fines increased the density. The opposite seemed true for No. 100 to No. 200 gap. For statistical comparisons, see Vol. II.

Stability and Gradation

Perhaps the best way to evaluate the effects of a grading change on Hveem stability is to compare the stability at a certain voids content, since most likely an optimum or maximum stability cannot be obtained by varying asphalt content as in conventional design procedures.

In this study the stability at 3% air voids was determined for each grading within each series (combination of aggregate type and asphalt penetration). These values (S_3) were used as basis for comparison. Tabulation of high and low stability at 3% air voids as well as those for well-graded mixes are given in Table 17. Hveem stability at 3% voids for Series B and F also provided a simple means of identifying the locations of "optimum" gaps for critical stability as well as effects of

Table 17. Stability of Hveem mixes at 3% voids vs grading and size.

Series	Size	High Grading	High Stability	I	F	P	Low Grading	Low Stability
B	3/4 in.	A-8	50	48	44	34	A-100	4
		A-4H	48					
		A-4L	47					
		A-4LH	46					
	1/2 in.	B-P	41			41	B-8	20
		B-100L	39					
		B-B	37					
	3/8 in.	C-I	41	41		21	C-P	21
		C-100L	38					
C	3/4 in.	A-F	59		59		A-8L	22
		A-100L	56					
	1/2 in.	B-100L	55			24	B-B	10
		B-8L	49					
	3/8 in.	C-30	50				C-30L	21
D	3/4 in.	A-4L	53	34		47	A-30	2
	1/2 in.	B-8	48				B-30	47
		B-30L	48					
	3/8 in.	C-I	52	52		43	C-100	18
F	3/4 in.	A-P	38			38	NG	20
		A-4	37				A-30L	20
		A-100L	37					

Table 18. Hveem stability at 3% voids vs location and method of gapping.

Series	Size	Above P Curve		Below P curve		P grading
B	A	4	43	4L	47	34
		8	50	8L	38	
		30	42	30L	41	
		100	4	100L	43	
	B	8	29	8L	28	41
		30	33	30L	30	
		100	30	100L	39	
	C	8	33	8L	32	21
		30	31	30L	31	
		100	33	100L	38	
F	A	4	37	4L	29	38
		8	36	8L	24	
		30	26	30L	20	
		100	26	100L	37	

b. Air voids at P_o $2 \leq Ap_o \leq 6$.

c. Cohesion at P_o: $Cp_o \geq 50$.

5. If properties of P_o meet all criteria, rank the mixture by SP_o.

6. If some of the properties do not meet the criteria, adjust SP_o by the following factors and rank by adjusted stability $SP'_o = SP_o \times R$:

$R = 0.75$ if fails 1 criterion,
$R = 0.50$ if fails 2 criteria,
$R = 0.25$ if fails 3 criteria.

B. Rank by the maximum stability S_m (if there is a peak stability).

C. Rank by stability S at 3% air voids (may be extrapolated) S_3.

D. Rank by weighted stability method (First approximation):

1. Determine stability at 3% air voids (may be extrapolated) S_3.

2. Determine weighted stability:

$$S_w = S_3 \cdot R_c$$

Cohesion	R_c
020-	0.8
021-050	0.9
051-100	1.0
101-200	1.1
201-400	1.2
401+	1.3

Series B (L_1 X 94 pen.)

By standard Asphalt Institute design procedure and criteria, only one (C-30) of the 33 gradings an acceptable mixture could not be produced. In other words, 26 out of 27 gap-graded aggregates in this series could produce satisfactory mixtures by standard criteria, which is very significant. The rankings of the gradings by various criteria for Series B are given in Table 19a. The best gradings for stability at the optimum asphalt content were: A-8, A-I, A-4H, A-8L, A-4L, A-4LH, B-B, B-P, C-8L, and C-I. It is to be noted that Iowa Type A gradings and British Standard 594 ranked high in respective sizes.

Comparison of mixes or gradings by stability at 3% air voids (method 3) is perhaps the most acceptable approach by current practice and contemporary thinking. The stability at 3% air voids (S_3) ranged from a low of 4 (A-100) to a high of 50 (A-8). Only 12 out of the 27

Table 19(a). Mix rankings by Hveem method — Series B.

		Criteria									
			1		2		3		4		
Batch No.	Gradation	P_o	SP_o	Rank	S_m	Rank	S_3	Rank	S_w	Rank	5
B001-005	B-8	4.4	37	11[b] (21)[c]	59	6[b] (11)	20	20 (35)	20	19 (34)	14.0
B006-010	A-30H	3.8	37	11[b] (21)	65	2[b] (16)	30	17[b] (25)	30	17 (25)	11.8
B011-015	B-P	3.9	45	7[b] (16)	52	12[b] (18)	41	8[b] (14)	45	6[b] (12)	8.3
B016-020	C-100	4.5	36	12 (12)	38	18 (29)	33	14[b] (22)	33	14[b] (22)	14.5
B021-025	C-100L	4.0	43	8[b] (17)	53	11[b] (17)	38	10[b] (17)	38	10[b] (18)	9.8
B026-030	B-30	3.9	40	9[b] (19)	62	3 (8)	33	14[b] (22)	33	14[b] (22)	10.0
B031-035	A-30L	3.9	43	8[b] (17)	46	17 (24)	41	8[b] (14)	45	6[b] (12)	9.8
B036-040	A-8	3.6	52	1 (10)	61	4[b] (9)	50	1 (6)	50	3 (7)	2.3
B041-045	A-I	4.5	50	2[b] (11)	56	8 (14)	48	2[b] (8)	53	1[b] (4)	3.3
B046-050	A-30LH	4.6	47	5[b] (14)	54	10[b] (16)	46	4[b] (10)	51	2[b] (6)	5.3
B051-055	A-F	4.0	46	6[b] (15)	48	16 (22)	44	5 (11)	44	7 (13)	8.5
B056-060	C-I	4.6	45	7[b] (16)	65	2[b] (6)	41	8[b] (14)	45	6[b] (12)	5.8
B061-065	A-8LH	3.3	43	8[b] (17)	55	9[b] (15)	39	9[b] (16)	43	8[b] (14)	8.5
B066-070	A-30	4.0	46	6[b] (15)	52	12[b] (18)	42	7 (13)	46	5 (11)	7.5
B071-075	A-4L	3.7	48	4[b] (13)	52	12[b] (18)	47	3 (9)	47	4[b] (10)	5.8
B076-080	A-4LH	3.3	48	4[b] (13)	50	14[b] (20)	46	4[b] (10)	51	2[b] (6)	6.0
B081-085	A-8H	4.2	46	6[b] (15)	61	4[b] (9)	35	12 (20)	38	10[b] (18)	8.0
B086-090	B-8L	4.4	35	13[b] (23)	59	6[b] (11)	28	18 (27)	31	16 (24)	13.3
B091-095	B-30L	5.1	35	13[b] (23)	52	12[b] (18)	30	17[b] (25)	33	14[b] (22)	14.0
B096-100	C-P	5.1	35	13[b] (23)	50	14[b] (20)	21	19 (34)	23	18 (31)	16.0
B101-105	B-B	5.2	48	4[b] (13)	66	1 (5)	37	11 (18)	37	11[b] (19)	6.8
B106-110	A-8L	4.4	49	3 (12)	54	10[b] (16)	38	10[b] (17)	42	9 (15)	8.0
B111-115	B-100L	4.4	43	8[b] (17)	52	12[b] (18)	39	9[b] (16)	43	8[b] (14)	9.3
B116-120	C-8L	4.7	48	4[b] (13)	51	13 (19)	32	15 (23)	32	15 (23)	11.8
B121-125	A-4H	4.3	50	2[b] (11)	50	14[b] (20)	48	2[b] (8)	53	1[b] (4)	4.8
B126-130	B-100	4.5	35	13[b] (23)	50	14[b] (20)	30	17[b] (25)	33	14[b] (22)	14.5
B131-135	C-8	5.1	38	10 (20)	53	11[b] (17)	33	14[b] (22)	36	12 (20)	11.8
B136-140	A-100L	4.0	48	4[b] (13)	57	7 (13)	43	6[b] (12)	47	4[b] (10)	5.3
B141-145	A-4	4.2	47	5[b] (14)	50	14[b] (20)	43	6[b] (12)	43	8[b] (14)	8.3
B146-150	C-30L	5.3	35	13[b] (23)	49	15 (21)	31	16[b] (24)	34	13[b] (21)	14.3
B151-155	A-P	4.5	40	9[b] (19)	55	9[b] (15)	34	13 (21)	37	11[b] (19)	10.5
B156-160	C-30	4.8	35[a]	14 (24)	52	12[b] (18)	31	16[b] (24)	34	13[b] (21)	13.8
B161-165	A-100	4.5	35	13[b] (23)	60	5 (10)	4	21 (38)	4	20 (37)	14.8

[a]Weighted stability at optimum asphalt content, $S'P_o$. [b]More than one mix with the same ranking.

[c]Numbers in parentheses indicate overall rankings in the four series.

gap gradings would have missed the minimum stability requirement of 35. So would the two FHWA gradings, A-P and C-P. Based on this criterion the "best" gradings were: A-8, A-4H, A-I, A-4L, A-4LH, A-30LH, B-P, B-100L, and C-I.

The maximum stability criterion (method 2) may not be very meaningful because, based on current concepts, the highest stability mixture may not be the most desirable mixture and, in many cases, there were no peaks when stability was plotted against asphalt content. However, since the Hveem stability does indicate one strength parameter: internal friction angle φ, this comparison may provide some indication of mixture quality. The gradings that yielded the highest maximum stabilities were: A-30H, A-8, B-B, B-30, C-I, and C-100L.

For reasons given earlier, evaluation of Hveem mixtures (gradings) by the weighted stability (S_w, method 4) Hveem stability at 3% voids adjusted by cohesion correction factors is believed to be the most logical, practical, and promising approach of evaluation when a number of mixtures with a wide range of aggregate type, size grading, and asphalt type are involved. The "best" gradings based on this method were: A-I, A-4H, A-30LH, A-4LH, A-8, A-4L, A-100L, A-30, A-30L, B-P, B-100L, C-I, and C-100L. Again Iowa Type A gradings (A-I, C-I) and B-P resulted in the best mixtures and the larger 3/4-in. mixtures seemed to out-rank either 1/2- or 3/8-in. mixtures.

Rankings by the average of the four sets of criteria (column 5, Table 19a) gave the following order of desirability of the gradings: A-8, A-I, A-4H, A-100L, A-30LH, A-4L, and C-I.

Series C (L_2 x 94 pen.)

All 17 gradings in this series yielded acceptable mixtures, based on the standard Asphalt Institute criteria. The rankings of the gradings by various criteria for Series C are given in Table 19b. The most desirable gradings by this method were: A-F, C-30, A-100L, A-8, B-100L, and A-30H.

The stability at 3% voids (S_3) ranged from a low of 10 (B-B) to a high of 59 (A-F). The higher ranked gradings were: A-F, A-100L, B-100L, A-30H, A-8, C-30, and B-8L.

Ranking of the gradings by the weighted stability showed that the "best" gradings in each size group were: A-F, A-100L, B-100L, B-8L, C-30, and C-100L. The overall rankings by the averages of the four rankings showed the highest ranked gradings were A-F, A-100L, A-8, C-30, and B-100L.

Series D (L_2 x 65 pen.)

All 17 gradings studied in this series yielded acceptable mixtures, based on the standard Asphalt Institute design criteria. The rankings of the gradings by various criteria are given in Table 19c. The "best" gradings were: A-4L, A-8H, A-P, B-30, B-8, C-I, and C-P.

Ranking by Hveem stability at 3% voids gave the following mixtures with the following gradings as the best mixtures: A-4L, C-I, B-8, B-30L, B-30, A-P, and C-P. Based on the maximum stability criterion, the higher ranked gradings were: A-30, C-100, A-I, B-30, A-30L, and A-4L.

Based on the weighted Hveem stability criterion, the "best" gradings were: A-4L, C-I, B-8, B-30L, B-30, and A-P. The highest average ranking gradings were: A-4L, C-I, and B-30.

Table 19(b). Mix rankings by Hveem method — Series C.

Batch No.	Gradation	Criteria 1 P_o	SP_o	Rank		Criteria 2 S_m	Rank		Criteria 3 S_3	Rank		Criteria 4 S_w	Rank		5
C001-005	C-100L	4.9	35	9[b]	(23)[c]	50	11[b]	(20)	25	9[b]	(30)	28	8	(27)	9.3
C006-010	B-P	5.0	35	9[b]	(23)	54	9[b]	(16)	24	10	(31)	26	10	(29)	9.5
C011-015	B-B	5.9	35	9[b]	(23)	46	12	(24)	10	14	(37)	11	15	(36)	12.5
C016-020	A-4	4.7	35	9[b]	(23)	53	10[b]	(17)	25	9[b]	(30)	25	11	(30)	9.8
C021-025	A-100	4.5	35	9[b]	(23)	73	1	(1)	–	–	–	–	–	–	5.0
C026-030	A-4LH	4.2	46	8	(15)	54	9[b]	(16)	42	7	(13)	42	7	(15)	7.8
C031-035	A-8L	3.4	35	9[b]	(23)	50	11[b]	(20)	22	12	(33)	22	13	(32)	11.3
C036-040	B-100L	4.5	58	5	(5)	61	8[b]	(9)	55	3	(3)	55	3	(3)	4.8
C041-045	A-30H	4.6	53	6	(9)	53	10[b]	(17)	53	4	(4)[b]	53	4	(4)[b]	6.0
C046-050	A-8	4.5	59	4	(4)	68	3	(3)	50	5[b]	(6)	50	5	(7)	4.3
C051-055	B-100	4.6	35	9[b]	(23)	66	5[b]	(5)	23	11	(32)	23	12	(31)	9.3
C056-060	C-30L	4.6	35	9[b]	(23)	61	8[b]	(9)	21	13	(34)	21	14	(33)	11.0
C061-065	C-8	4.7	35	9[b]	(23)	67	4	(4)	27	8	(28)	27	9	(28)	7.5
C066-070	A-F	4.2	67	1	(1)	70	2	(2)	59	1	(1)	59	1	(1)	13.0
C071-075	B-8L	4.4	52	7	(10)	65	6	(6)	49	6	(7)	49	6[b]	(8)	6.3
C076-080	A-100L	4.2	60	3	(3)	63	7	(7)	56	2	(2)	56	2	(2)	3.5
C081-085	C-30	5.2	61	2	(2)	66	5[b]	(5)	50	5[b]	(6)	50	6[b]	(7)	4.5

[b] More than one mix with the same ranking.

[c] Numbers in parentheses indicate overall rankings in the four series.

Table 19c. Mix rankings by Hveem method — Series D.

Batch No.	Grad-ation	Criteria 1				Criteria 2			Criteria 3			Criteria 4			5
		P_o	SP_o	Rank		S_m	Rank		S_3	Rank		S_w	Rank		
D001-005	A-I	3.7	45	9	(16)[c]	60	3[b]	(10)	34	11	(21)	34	11	(21)	8.5
D006-010	C-I	4.0	57	1[b]	(6)	57	5[b]	(13)	52	2	(5)	52	2	(5)	2.5
D011-015	B-8	4.0	52	4	(10)	55	6	(15)	48	3[b]	(8)	48	3[b]	(9)	4.0
D016-020	B-30	3.7	55	2	(7)	60	3[b]	(10)	47	4[b]	(9)	47	4[b]	(10)	3.3
D021-025	A-30L	3.3	47	7[b]	(14)	60	3[b]	(10)	42	6	(13)	42	6	(15)	5.5
D026-030	C-100	4.7	42	10	(18)	66	2	(5)	18	12	(36)	18	12	(35)	9.0
D031-035	A-8LH	3.0	35	12[b]	(23)	42	11	(28)	40	8	(15)	40	8	(17)	9.8
D041-045	C-P	3.5	54	3	(8)	58	4	(12)	43	5	(12)	43	5	(14)	4.3
D046-050	B-30L	4.1	49	5[b]	(12)	49	9	(21)	48	3[b]	(8)	48	3[b]	(9)	5.0
D051-055	C-8L	4.2	46	8	(15)	53	7	(17)	38	9[b]	(17)	38	9[b]	(18)	8.3
D056-060	A-4H	3.6	47	7[b]	(14)	52	8	(18)	41	7	(14)	41	7	(16)	7.3
D061-065	A-4L	3.2	57	1[b]	(6)	60	3[b]	(10)	53	1	(4)	53	1	(4)[b]	1.5
D066-070	A-8H	3.4	49	5[b]	(12)	57	5[b]	(13)	38	9[b]	(17)	38	9[b]	(18)	7.0
D071-075	A-30LH	3.8	40	11	(19)	48	10[b]	(22)	37	10[b]	(18)	37	10	(19)	10.3
D076-080	A-P	2.8	48	6	(13)	48	10[b]	(22)	47	4[b]	(9)	47	4[b]	(10)	6.0
D081-085	A-30	3.9	35	12[b]	(23)	67	1	(4)	2	13	(39)	2	13	(38)	9.8

[b] More than one mix with the same ranking.

[c] Numbers in parentheses indicate overall rankings in the four series.

The gradings that showed consistently high rankings in this series were: A-4L, A-P, B-8, C-I, and C-P.

Series F (G x 91 pen.)

The obvious observation on this series of mixes is the relatively low stability compared with the mixes made with crushed limestones. Two of the 10 non-well-graded aggregates could not produce satisfactory mixes by the Asphalt Institute criteria. The rankings of the various gradings are given in Table 19d. The best gradings for the stability at optimum asphalt content appeared to be: A-P, A-4, A-8, and A-100L.

Based on a stability at 3% air voids the top ranked gradings were: A-P, A-4, A-100L, and A-8. Those based on maximum stability were: A-4, A-100, A-100L, and A-P.

Rankings, based on weighted stability at 3% air voids, that showed the best gradings in this series were: A-P, A-100L, A-8, and A-4. The overall rankings (average of the four ranks) showed that the most desirable gradings were: A-P, A-4, and A-100L.

Rankings of Hveem Mixes Between Series

The top ten gradings, when all 78 gradings in four series were compared, are given in Table 20. The following general observations can be made:

- Series C mixes dominated the higher ranked mixes.
- Out of 33 gradings studied 14 appeared in the table more than once; 10 of the 14 were gap-graded mixes.
- The gradings that appeared in the table most frequently were: A-8 (5), A-F (3), A-4L (3), A-30H (3), A-100L (3), B-100L (3), C-I (3), and C-F (3). The well-graded Iowa grading A-I and FHWA grading C-P each appeared in the top ten once.

Table 19d. Mix rankings by Hveem method — Series F.

Batch No.	Grad-ation	Criteria 1			Criteria 2		Criteria 3		Criteria 4		5
		P_o	SP_o	Rank	S_m	Rank	S_3	Rank	S_w	Rank	
F001-05	A-4	4.2	42	1[b] (18)[c]	55	1 (15)	37	2[b] (18)	37	4 (19)	2.0
F006-10	A-4L	4.0	36	2 (22)	44	6[b] (26)	29	5 (26)	32	6 (23)	4.8
F011-15	A-8	4.1	42	1[b] (18)	47	4 (23)	36	3 (19)	40	3 (17)	2.8
F016-20	A-8L	3.6	35	3[b] (23)	42	7 (27)	24	7 (31)	26	8 (29)	6.3
F021-25	A-30	3.8	35	3[b] (23)	44	6[b] (26)	26	6[b] (29)	29	7[b] (26)	5.5
F026-30	A-30L	3.7	35 (26)[a]	4 (24)	45	5 (25)	20	8[b] (35)	20	9[b] (34)	6.5
F031-35	A-100	4.4	35	3[b] (23)	51	2 (19)	26	6[b] (29)	29	7[b] (26)	4.5
F036-40	A-100L	5.1	42	1[b] (18)	50	3[b] (20)	37	2[b] (18)	41	2 (18)	2.0
F041-45	NG	5.1	23 (17)[a]	5 (25)	26	9 (31)	20	8[b] (35)	20	9[b] (34)	7.8
F046-50	B-B	6.4	35	3[b] (23)	35	8 (30)	33	4 (22)	36	5 (20)	5.0
F051-55	A-P	4.4	42	1[b] (18)	50	3[b] (20)	38	1 (17)	42	1 (15)	1.5

[a] Weighted stability at optimum asphalt content, $S'P_o$.

[b] More than one mix with the same ranking.

[c] Numbers in parentheses indicate overall rankings in the four series.

Table 20. Top ranked mixes of all mixes — Hveem procedure.

Ranking	1 — SP_o	2 — S_3	3 — S_w
1	(C) A-F	(C) A-F	(C) A-F
2	(C) C-30	(C) A-100L	(C) A-100L
3	(C) A-100L	(C) B-100L	(C) B-100L
4	(C) A-8	(C) A-30H	(B) A-I; (C) A-30H
5	(C) B-100L	(D) A-4L	(B) A-4H
6	(D) C-I	(D) C-I	(C) A-30H
7	(D) A-4L	(D) C-30	(D) A-4L
8	(D) B-30	(B) C-30	(D) C-I
9	(D) C-P	(C) A-8	(B) A-30LH
10	(C) A-30H	(C) B-8L	(B) A-8; (C) A-8
			(C) C-30

Mixture Design and Evaluation — Marshall vs Hveem

Though outside the scope of this investigation, data obtained in this work provide ready comparison between mix design and evaluation by the two procedures. By comparing data in Tables 13 and 19, and Tables 14 and 21, the following observations can be made:

1. The optimum asphalt contents determined by the two procedures were usually different; those determined by Marshall method were somewhat higher in most cases.

Table 21a. Rankings of Hveem mixes by series and size - Series B.

Size	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Ranking
A (3/4 in.)	A-8	A-30H	A-8	A-I	1
	A-I	A-8	A-4H	A-4H	2
	A-4H	A-8H	A-I	A-4LH	3
	A-8L	A-100	A-4L	A-30LH	4
	A-4L	A-100L	A-4LH	A-8	5
	A-4LH	A-I	A-30LH	A-4L	6
	A-100L	A-P	A-F	A-100L	7
	A-30LH	A-8LH	A-100L	A-30	8
	A-4	A-30LH	A-4	A-30L	9
	A-F	A-8L	A-30	A-F	10
	A-30	A-30	A-30L	A-8LH	11
	A-8H	A-4L	A-8LH	A-4	12
	A-30L	A-4LH	A-8L	A-8L	13
	A-8LH	A-4H	A-8H	A-8H	14
	A-P	A-4	A-P	A-P	15
	A-30H	A-F	A-30H	A-30H	16
	A-100	A-30L	A-100	A-100	17
B (1/2 in.)	B-B	B-B	B-P	B-P	1
	B-P	B-30	B-100L	B-100L	2
	B-100L	B-8	B-B	B-B	3
	B-30	B-8L	B-30	B-30	4
	B-8	B-P	B-100	B-30L	5
	B-8L	B-30L	B-30L	B-100	6
	B-30L	B-100L	B-8L	B-8L	7
	B-100	B-100	B-8	B-8	8
C (3/8 in.)	C-8L	C-I	C-I	C-I	1
	C-I	C-100L	C-100L	C-100L	2
	C-100L	C-8	C-8	C-8	3
	C-8	C-30	C-100	C-30	4
	C-100	C-8L	C-8L	C-30L	5
	C-P	C-P	C-30L	C-100	6
	C-30L	C-30L	C-30	C-8L	7
	C-30	C-100	C-P	C-P	8

Ranking of Hveem mixes by series and size — Series D.

Criteria 1	2	3	4	Ranking
A-4L	A-30	A-4L	A-4L	1
A-8H	A-I	A-P	A-P	2
A-P	A-30L	A-30L	A-30L	3
A-4H	A-4L	A-4H	A-4H	4
A-30L	A-8H	A-8LH	A-8LH	5
A-I	A-4H	A-8H	A-8H	6
A-30LH	A-30LH	A-30LH	A-30LH	7
A-30	A-P	A-I	A-I	8
A-8LH	A-8LH	A-30	A-30	9
B-30	B-30	B-8	B-8	1
B-8	B-8	B-30L	B-30L	2
B-30L	B-30L	B-30	B-30	3
C-I	C-100	C-I	C-I	1
C-P	C-P	C-P	C-P	2
C-8L	C-I	C-8L	C-8L	3
C-100	C-8L	C-100	C-100	4

Ranking of Hveem mixes by series and size — Series F.

Criteria 1	2	3	4	Ranking
A-4	A-4	A-P	A-P	1
A-8	A-100	A-4	A-100L	2
A-100L	A-100L	A-100L	A-8	3
A-P	A-P	A-8	A-4	4
A-4L	A-8	A-4L	A-4L	5
A-8L	A-30L	A-30	A-30	6
A-30	A-4L	A-100	A-100	7
A-100	A-30	A-8L	A-8L	8
A-30L	A-8L	A-30L	A-30L	9
NG	NG	NG	NG	10
B-B	B-B	B-B	B-B	1

this field. In the questionnaire (Appendix H), the judges were asked to rate 50 hypothetical Marshall mixtures and 40 hypothetical Hveem mixtures based on given properties of random combinations of 5 levels of stability, 5 levels of flow, 5 levels of air voids, 3 levels of VMA (or voids filled), 3 levels of film thickness, and 2 levels of penetration of asphalt for Marshall mixes and 3 levels of stability, 4 levels of cohesion, 4 levels of air voids, 3 levels of swell, 3 levels of average film thickness, and 2 levels of asphalt penetration for Hveem mixes.

To date, not counting those asking to be excused from such a task, twenty-five returns were received. Seven of them either do not believe Marshall or Hveem procedures can be used to evaluate mix quality (beyond optimum asphalt content determinations) or do not believe there was sufficient or satisfactory information contained in the questionnaires for quality ranking. Eighteen judges ranked either Marshall or Hveem mixes or both. As pointed out by some of the responses, the questionnaires were far from perfect or realistic. It is believed, nevertheless, that this approach has the potential of quantitative overall evaluation of wide range of asphalt mixes based on conventional design method and perhaps in production control and specification writing.

Presented in the following sections are illustrations of how quality index models or rating functions can be developed from this questionnaire, and how such index or functions can be used for asphalt mixture quality evaluation and rating when wide ranges of aggregate gradation, type, size, asphalt type, and content are involved.

Section 1. Penalty Functions, Joint Penalty Functions, Rating Functions, Grand Rating Functions, and Dispersion Functions

One approach used in attempting to determine the relative worth of the many mixtures studied involved sending a questionnaire to about 30 experts in the field, asking them to assign numerical ratings from 1-10 to 50 hypothetical Marshall mixtures and 40 hypothetical Hveem mixtures. By the term hypothetical Marshall mixtures we mean a listing of hypothetical values for stability, flow, voids, VMA, voids filled, average film thickness, and penetration of asphalt. For example, the first Marshall mixture was designed as having a stability of 3000, a flow of 16, a voids percent of 1, a VMA percent of 14, a voids filled percent of 90*, an average film thickness of 5 μ and a penetration of asphalt of 100. Similarly, by a hypothetical Hveem mixture we mean a listing of hypothetical values of stability, cohesion, voids percent, swell, average film thickness, and penetration of asphalt. Again, as an example, the first Hveem mixture included in the survey was described as having a stability of 65, a cohesion of 40, a voids percent of 4, a swell of 0.03 in., average film thickness of 5 μ, and a penetration of asphalt of 60. (The properties of all hypothetical mixtures are given in Appendix H.)

All 50 Marshall mixtures were concocted by choosing at random from among the following five levels of stability: 400, 500, 1000, 3000, and 5000. Similarly, flow values were chosen at random, independently of

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*Given values of voids percent, VMA percent, and voids filled percent were not consistent and experts were left to choose the two out of three properties considered relevant.

the stability choices from among the five flow values of 5, 8, 12, 16, and 24. Similarly, percentage of voids were chosen at random and independently from among the values 1, 2, 3, 4, and 8%. VMA values were randomly selected from 10, 14, and 18. Voids filled percents were randomly selected from the values 70, 80, and 90. Average film thicknesses were randomly selected from the levels 5, 10, and 15. Penetration of asphalt were randomly selected from the two levels 60 and 100.

The hypothetical 40 Hveem mixtures were randomly selected in an analogous way. Stability was randomly selected from among the levels 25, 45, and 65. Cohesion was randomly selected from the levels 40, 60, 100, and 400. Voids percent were randomly selected from among the levels 2, 3, 4, and 8. Levels of swell were randomly selected from 0.01, 0.03, and 0.05 in. Average film thicknesses were randomly selected from among the levels 5, 10, and 15 μ. And again, penetration of asphalt was chosen from the levels 60 and 100.

Judges were asked to consider that each of the 50 hypothetical Marshall mixtures was in fact a real mixture on which Marshall tests had been run, yielding the indicated figures for stability, flow, two of the three voids measures, and so on. Judges were asked to rate these 50 mixtures by the numbers 1 through 10, 1 indicating a mixture that is totally unacceptable. 10 indicating a mixture which would be ideal and 4 indicating a mixture that would be acceptable. Similar ratings were asked of the judges for the 40 Hveem mixtures. Note that in the case of the Marshall mixtures it was expected that judges would, as indeed most did, identify which two of the three indices voids, VMA, and voids filled they had considered in their ranking. In addition, judges were asked to rate the properties (7 properties in the case of the Marshall mixtures and 6 properties in the case of the Hveem mixtures) from 0 to 4 in accordance with the relative importance of these properties as they had entered their rating of the 50, respectively 40, mixtures. Finally judges were also asked to identify groupings of properties that they had considered jointly rather than independently in arriving at their assessments. A good example of a response in that direction is provided by one of the judges who pointed to stability and flow as properties to be jointly, feeling that high levels of stability occurring jointly with high levels of flow could be expected to lead to good mixtures, as would mixtures featuring intermediate levels of stability and flow, whereas mixtures with high stability and low flow or low stability and high flow would be less desirable.

All returned questionnaires are intended for use in the construction of an index of merit. In particular it is hoped to proceed in the following fashion, considering for example the Marshall mixtures.

A. Consider the Marshall mixtures rated by the judges. A first step in the construction of a rating scheme is to subject all returns to some study of internal consistency. In the second section of this chapter is indicated how such a consistency check might proceed; such a check is illustrated by citing a returned questionnaire where a certain amount of apparent inconsistency was detected.

B. All the Marshall questionnaires found not to be clearly inconsistent are now candidates for the construction of the index. One takes a particular questionnaire and attempts to mathematically describe the type of rating philosophy that the particular judge has employed. One is helped in this mathematical modeling of a particular judge by the actual ratings that he has assigned to the hypothetical Marshall mixtures, by his comments regarding the relative importance of the seven properties listed, and by the information given about the manner in which grouping considerations entered his judgment. In most cases it was found adequate to work with a certain "workhorse" model (mathematical form) of the rating of a given judge based on a certain multiplicative postulate: one postulates the existence of what might be called a penalty function corresponding to each of the Marshall properties. A penalty function for a given attribute, say stability, is one that is 0 over a certain ideal range and then falls (linear decline is usually adequate) as the attribute moves away from this range. Such a penalty function, then, gives both an optimal zone of a given factor and also the seriousness of departures of all magnitudes from the optimal zone. Once a penalty function is deduced for all factors, one implements the multiplicative hypothesis about judge ratings by thinking of the sum of all seven penalty functions as an exponent of a convenient positive number, say the number e, or the number 16 that we happened to find convenient, and think of 16, raised to this sum of all penalty functions, as the rating function of a given judge. A final multiplication by 10 puts the rating in the desired numerical range. Thus, summarizing the remarks made so far, if one considers a given judge rating

Marshall mixtures, the simple "workhorse" model for the ratings of that judge is a rating function of the form 10 times 16 raised to a certain exponent, that exponent being the sum of certain penalty functions; each of these penalty functions pertains to a given Marshall property and is 0 in the optimal range of that property, decreasing away from the optimal zone in proportion to the seriousness with which deviations from the optimal zone are conceived by the judge in question.

Note that, though this simple workhorse multiplicative model seemed adequate for several of the judge responses investigated, there are cases, as is illustrated below, when the grouping statements of a certain judge and his actual ratings are such that two or perhaps three factors cannot be modeled independently of each other, as is done by the multiplicative model; matters must then be complicated by attempting to formulate a joint penalty function involving these two or three properties. Such a function is shown in Fig. 14 on page 107 for stability and flow. Joint penalty functions are again multiplied by all other penalty functions, these latter being typically of only the ordinary single-property type. In the extreme, very complex rating functions composed of multiplicative pieces pertaining to property groups are envisionable.

Once a rating function has been constructed for every judge not initially disqualified for inconsistency, the rating functions of all such judges are averaged, yielding a <u>grand rating function</u> $\overline{R}$ $(x_1, \ldots, x_7)$.

Accompanying the grand rating function is a function that might be described as the dispersion function, which could be computed in accordance with any of a number of standard measures of dispersion; for example, the standard deviation or the mean deviation. If we focus on the standard deviation for purposes of illustration, the dispersion function is simply the standard deviation of all the rating functions entering the grand rating function. In other words, if we denote the several individual rating functions by $R_1(x_1, x_2, \ldots, x_7)$, $R_2(x_1, x_2, \ldots, x_7)$, ... and if we assume that there are J judges, then the dispersion function is given by the formula

$$D(x_1, \ldots, x_7) = \frac{[\sum_{j=1}^{J} (R_j(x_1, \ldots, x_7) - \overline{R}(x_1, \ldots, x_7))^2]^{1/2}}{J - 1}$$

where $\overline{R}(x_1, \ldots, x_7) = \sum_{j=1}^{J} R_j(x_1, \ldots, x_7)/J$ and equals the grand rating function. One would hope to utilize the dispersion function in conjunction with the grand rating function as follows: significance is attached to the rating given by the grand rating function in accordance with values assumed by the dispersion function. If, for a given actual mixture, the grand rating function assigns say the rating 7.5, and if the dispersion function is relatively small, say 2, then a high degree of belief is assigned to the rating 7.5 indicated by the grand rating function. On the other hand, if the grand rating function were to assign the same number 7.5 to a certain actual mixture, but the dispersion function were large, say of the order of 4 or 5, then one would tend not to attach a great deal of significance to the rating indicated by the grand rating function, since the high value of the dispersion function would indicate that there had not been good agreement among the judges contributing to the grand rating function. The next sections give details of the various matters broached above; particularly on the manner in which the construction of the rating function of a given judge proceeds, both when the simple multiplicative model seems adequate and when, in case it is not, one must go to a joint penalty specification.

Section 2. Illustration of An Inconsistency Check

To illustrate the problem of inconsistency, consider the following Hveem ratings given by one of the judges:

	Stability	Cohesion	Voids	Swell	Rating
1.	25	400	2	0.03	10
2.	25	60	3	0.01	8
3.	25	400	3	0.01	6
4.	25	40	2	0.03	6
5.	25	100	3	0.03	5
6.	25	100	3	0.05	5
7.	25	400	2	0.05	5

Comparing mixtures 1 and 4, one finds that a value of cohesion of 400 is rated substantially above a value of 40. Yet comparing mixtures 2 and 3, one finds that a mixture with a cohesion of 60 is rated above another otherwise identical mixture with a cohesion of 400.

Again, comparing 5 and 6, one finds that a mixture with a swell value of 0.03 is rated equal to another mixture with a value of 0.05. Yet, comparing 1 and 7, we find that a swell value of 0.03 is rated much above 0.05.

Section 3. Illustration of the Construction of a Multiplicative Rating Function

This section illustrates the construction of a Hveem rating function, using the ratings given in Table 23.

Table 23. Ratings of Hveem mixes by Judge F.

Mix No.	Stability, lb, S	Cohesion, C	Voids, %, V	Swell, in.	Ave film thickness, μ	Pen. of asphalt	Mix rating R
1	65	40	4	0.03	5	60	3
2	25	400	2	0.03	15	100	6
3	65	100	8	0.01	15	60	3
4	65	40	8	0.05	10	100	2
5	25	40	3	0.05	10	60	1
6	65	400	4	0.03	15	100	5
7	45	400	4	0.03	10	100	9
8	45	60	8	0.01	10	60	3
9	45	100	2	0.03	10	100	4
10	65	100	4	0.01	10	60	5
11	65	40	8	0.01	15	60	2
12	25	400	3	0.01	10	60	5
13	45	60	8	0.05	15	60	2
14	25	60	4	0.01	10	100	4
15	45	400	2	0.03	5	100	4
16	25	100	3	0.03	5	100	4
17	45	100	4	0.03	10	60	8
18	45	400	2	0.01	5	60	4
19	25	400	4	0.03	10	100	5
20	65	60	3	0.01	5	100	3
21	25	60	4	0.05	15	100	2

Table 23. Continued.

Mix No.	Stability, lb, S	Cohesion, C	Voids, %, V	Swell, in.	Ave film thickness, μ	Pen. of asphalt	Mix rating R
22	25	40	2	0.03	15	100	2
23	65	60	4	0.05	10	100	4
24	65	100	2	0.03	15	100	5
25	45	40	3	0.01	5	100	3
26	25	100	3	0.05	15	60	3
27	65	400	2	0.05	5	60	2
28	45	40	8	0.03	15	60	3
29	65	400	4	0.03	15	60	6
30	25	60	4	0.01	10	100	4
31	45	400	4	0.01	10	60	9
32	45	100	3	0.01	5	100	5
33	65	60	8	0.05	10	100	1
34	25	60	8	0.01	5	100	2
35	45	100	3	0.01	5	60	5
36	65	100	2	0.05	15	100	2
37	45	60	8	0.03	15	60	3
38	25	400	2	0.05	15	60	5
39	45	100	4	0.03	5	100	5
40	65	100	3	0.03	10	60	6
Property importance rating	3	3	4	4	2	2	

The principal idea is to start with the highest ratings, to establish the "optimal zones," and then go to the somewhat lower ratings, which typically are somewhat lower because of the deviation from optimality of a <u>single property</u>. This enables one to deduce the penalties due to deviations from optimality of individual properties. Mixes with still lower scores allow adjustments of penalty functions already derived, or the estimation of new penalty functions, when the rating has been depressed by nonoptimal levels of two properties, of which one has already been analyzed.

For the judge in question penalty functions estimated for stability, cohesion, voids, and swell are given in Fig. 13a to 13d, the other two properties were considered relatively unimportant by this judge.

The rating function R is computed as follows:

$$R(S, C, V, s) = (10)\, 16^{[f(S) + g(C) + H(V) + k(s)]}$$

It is of course of interest to assess how well the rating function is able to simulate the actual ratings of the judge involved. To this end Table 24 compares actual with computed ratings for the first 16 mixtures.

Section 4. Illustration of the Construction of a Joint Penalty Function and Corresponding Rating Function

The construction of a joint Marshall penalty function is now illustrated by using the ratings given in Table 25. (Note that the judge involved based his voids assessments on Voids and Voids filled only.)

Except that a joint penalty function has been derived for stability and flow, the general technique is the same as above, with the higher ratings providing the primary penalty cues.

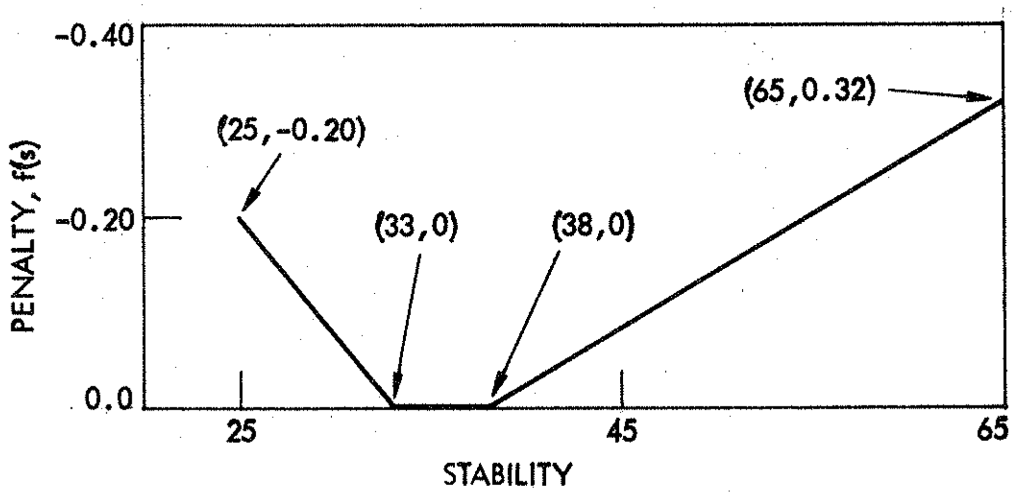

Fig. 13a. Stability penalty function f(s), $25 \leq s \leq 65$.

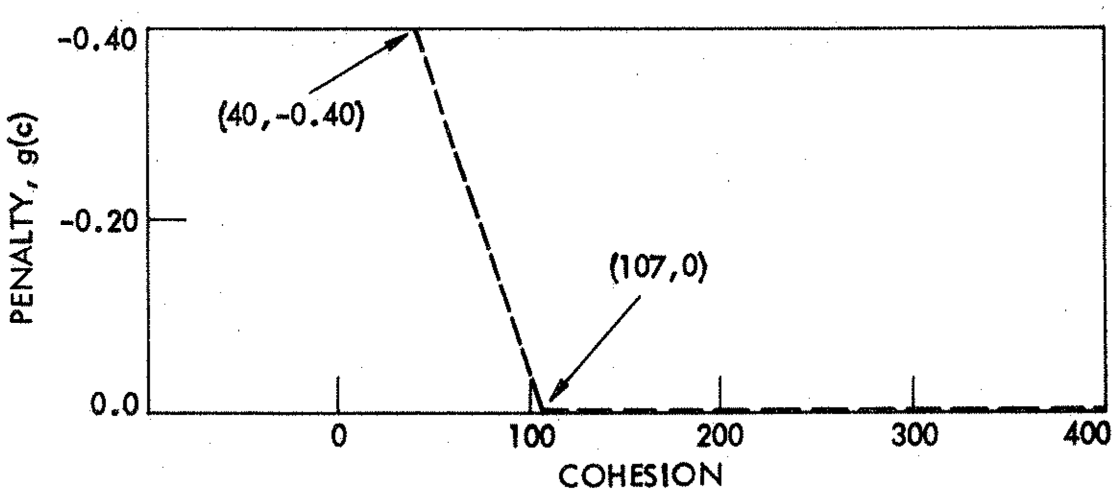

Fig. 13b. Cohesion penalty function g(c), $40 \leq c \leq 400$.

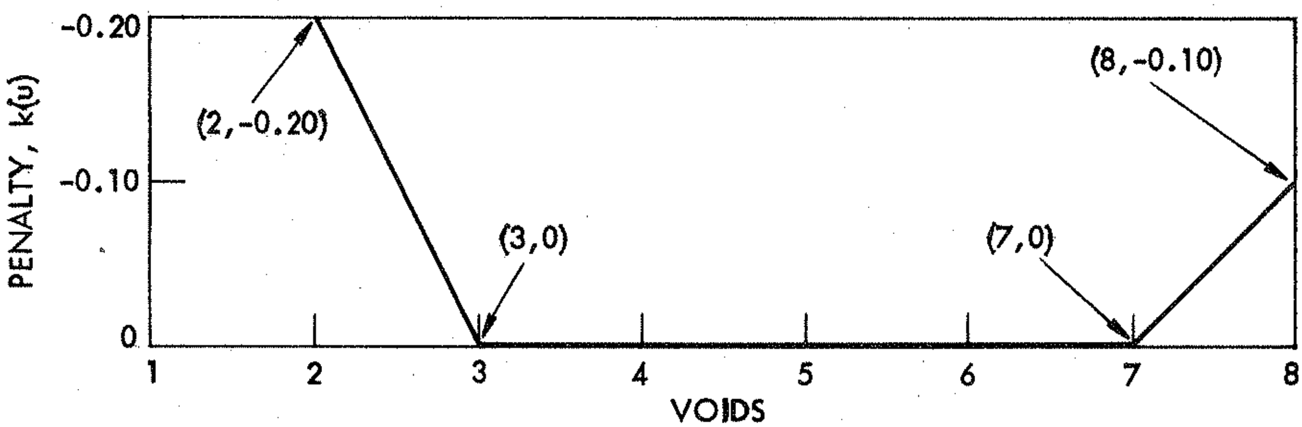

Fig. 13c. Voids penalty function h(V), $2 \leq V \leq 8$.

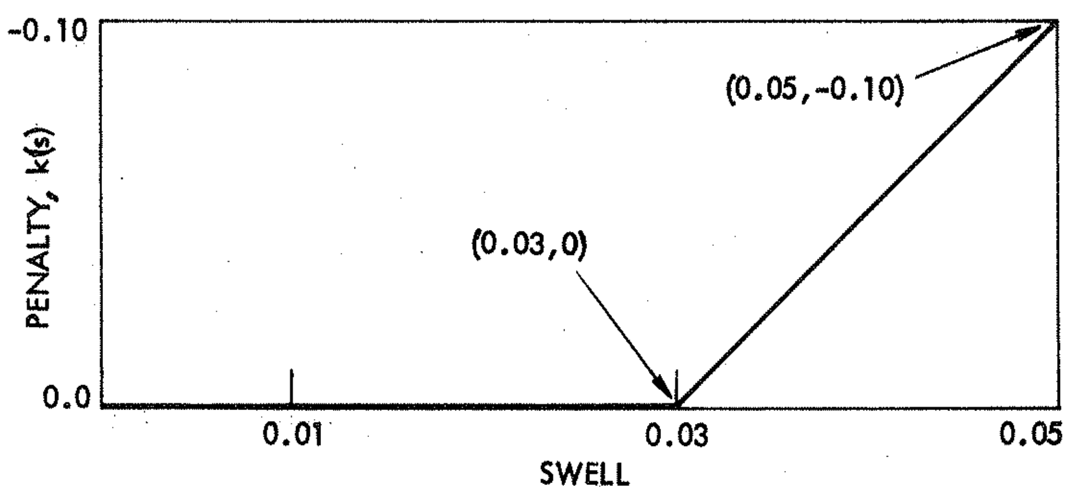

Fig. 13d. Swell penalty function k(s), $0 \leq s \leq 0.05$.

Table 24. Comparison of R (S, C, V, s) with actual ratings by Judge F.

Mix No.	Stability, lb, S	Cohesion, C	Voids, %, V	Swell, in., s	f(S)	9(C)	h(V)	k(s)	R(S,C,V,s)	Actual rating
1	65	40	4	0.03	-0.32	-0.40	0.00	0.00	2	3
2	25	400	2	0.03	-0.20	-0.00	-0.20	0.00	4	6
3	65	100	8	0.01	-0.32	-0.04	-0.10	0.00	3	3
4	65	40	8	0.05	-0.32	-0.40	-0.10	-0.10	1	2
5	25	40	3	0.05	-0.20	-0.40	0.00	-0.10	2	1
6	65	400	4	0.03	-0.32	0.00	0.00	0.00	4	5
7	45	400	4	0.03	-0.08	0.00	0.00	0.00	8	9
8	45	60	8	0.01	-0.08	-0.28	-0.10	0.00	3	3
9	45	100	2	0.03	-0.08	-0.04	-0.20	0.00	4	4
10	65	100	4	0.01	-0.32	-0.04	0.00	0.00	4	5
11	65	40	8	0.01	-0.32	-0.40	-0.10	-0.10	1	2
12	25	400	3	0.01	-0.20	0.00	0.00	0.00	6	5
13	45	60	8	0.05	-0.08	-0.28	-0.10	-0.10	2	2
14	25	60	4	0.01	-0.20	-0.28	0.00	0.00	3	4
15	45	400	2	0.03	-0.08	0.00	-0.20	0.00	5	4
16	25	100	3	0.03	-0.20	-0.04	0.00	0.00	5	4

Table 25. Ratings of Marshall mixes by Judge K.

Mix No.	Stability, lb, S	Flow, 0.01 in, F	Voids, %, V	VMA, %	Voids filled, %, S	Ave film thickness, μ	Pen. of asphalt	Mix rating, R
1	3000	16	1	14	90	5	100	2
2	1000	5	1	10	90	15	60	2
3	3000	12	3	18	70	15	100	9
4	5000	12	1	10	90	10	100	3
5	500	8	3	10	80	15	60	1
6	5000	16	1	18	90	5	100	2
7	1000	24	1	14	70	15	60	1
8	500	24	4	18	90	10	100	1
9	5000	8	3	10	70	15	60	8
10	1000	16	2	14	90	10	60	3
11	500	24	3	10	90	15	100	1
12	5000	5	8	18	90	15	60	3
13	1000	5	8	18	80	10	60	3
14	3000	24	8	10	90	5	100	2
15	3000	12	1	14	80	10	100	2
16	3000	16	1	18	90	5	100	2
17	5000	12	4	10	70	5	60	9
18	3000	16	3	14	70	15	60	9
19	1000	12	4	14	80	10	60	3
20	3000	24	3	14	90	10	100	2
21	1000	12	1	10	90	5	100	2
22	400	12	8	10	90	5	100	1
23	3000	16	1	14	90	15	60	2
24	1000	5	2	14	70	10	60	3
25	500	24	4	10	90	15	60	1
26	5000	8	3	18	90	10	100	3
27	5000	24	4	14	70	10	60	2
28	500	16	3	10	70	5	100	1
29	5000	8	8	10	70	15	100	3

Table 25. Continued.

Mix No.	Stability, lb, S	Flow, 0.01 in, F	Voids, %, V	VMA, %	Voids filled, %, S	Ave-film thickness, μ	Pen. of asphalt	Mix rating,
30	500	12	4	10	90	15	100	1
31	5000	5	1	18	90	5	100	2
32	400	5	1	14	70	15	60	1
33	3000	8	3	14	90	5	100	3
34	500	24	1	18	80	15	100	1
35	400	16	2	14	90	10	100	1
36	500	16	4	10	70	10	100	1
37	5000	16	8	10	90	5	60	3
38	400	8	8	18	80	5	100	1
39	400	24	3	10	80	15	60	1
40	400	12	1	14	90	15	60	1
41	500	5	4	10	80	10	60	1
42	3000	8	2	14	90	10	100	3
43	5000	12	4	14	90	5	60	3
44	5000	24	1	18	90	10	60	1
45	1000	24	8	18	90	5	100	1
46	5000	5	2	18	90	5	100	2
47	3000	16	3	18	90	10	100	3
48	500	12	2	10	90	5	60	1
49	1000	5	3	10	90	15	100	2
50	500	12	8	18	80	15	60	1
Property importance rating								

The joint penalty function of stability and flow actually is given not as a penalty but rather as an (S,F) score or rating, denoted by t. Figure 14 indicates the geometric nature of this (S,F) — score t, and Fig. 15 shows how t might be computed algorithmically by machine. Figure 14 also shows the various regions involved in the algorithmic locating of the point (S,F) prior to calculating an (S,F) — score t, for $0 \le S \le 5000$ and $0 \le F \le 24$.

(a) In region IX, with boundaries

$$\frac{F - 8}{S - 1240} = \frac{1}{2080},$$

$$\frac{F - 12}{S - 1240} = \frac{1}{587},$$

$$S = 1240,$$

the (S,F) — score t equals 10.

(b) In regions V and X, which together comprise an (S,F) region with boundaries

$$\frac{F - 12}{S - 1240} = \frac{1}{587},$$

$$\frac{F - 18}{S - 1240} = \frac{1}{587},$$

$$\frac{F - 17.32}{S - 840} = -0.0133,$$

the (S,F) — score t is given by

$$\frac{F - 6(3 - (0.1)(t))}{S - 1240} = \frac{1}{587} .$$

(c) In region IV, with boundaries

$$\frac{F - 17.32}{S - 840} = -0.0133,$$

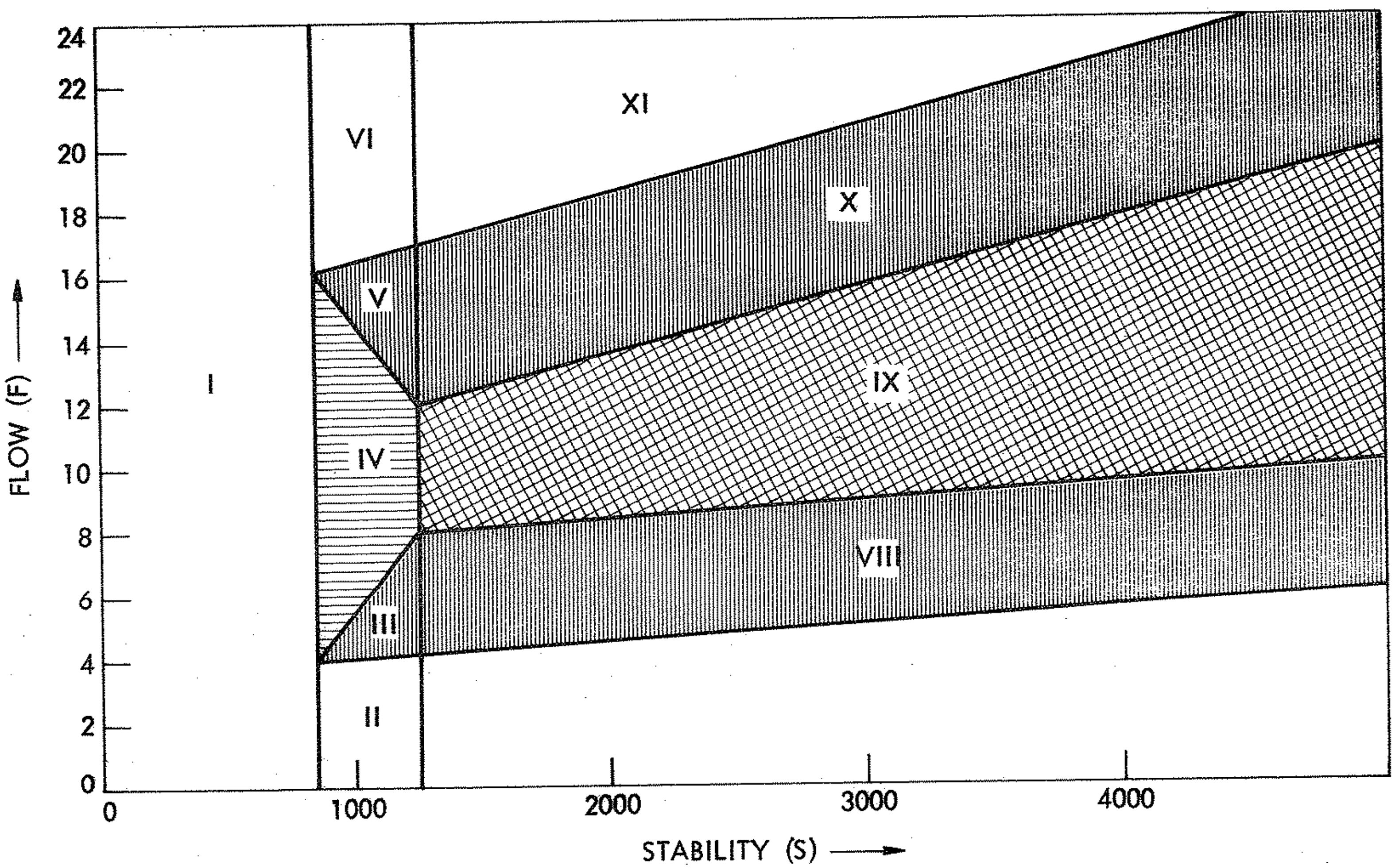

Fig. 14. Regions of definition of the bivariate (S, F) - score t.

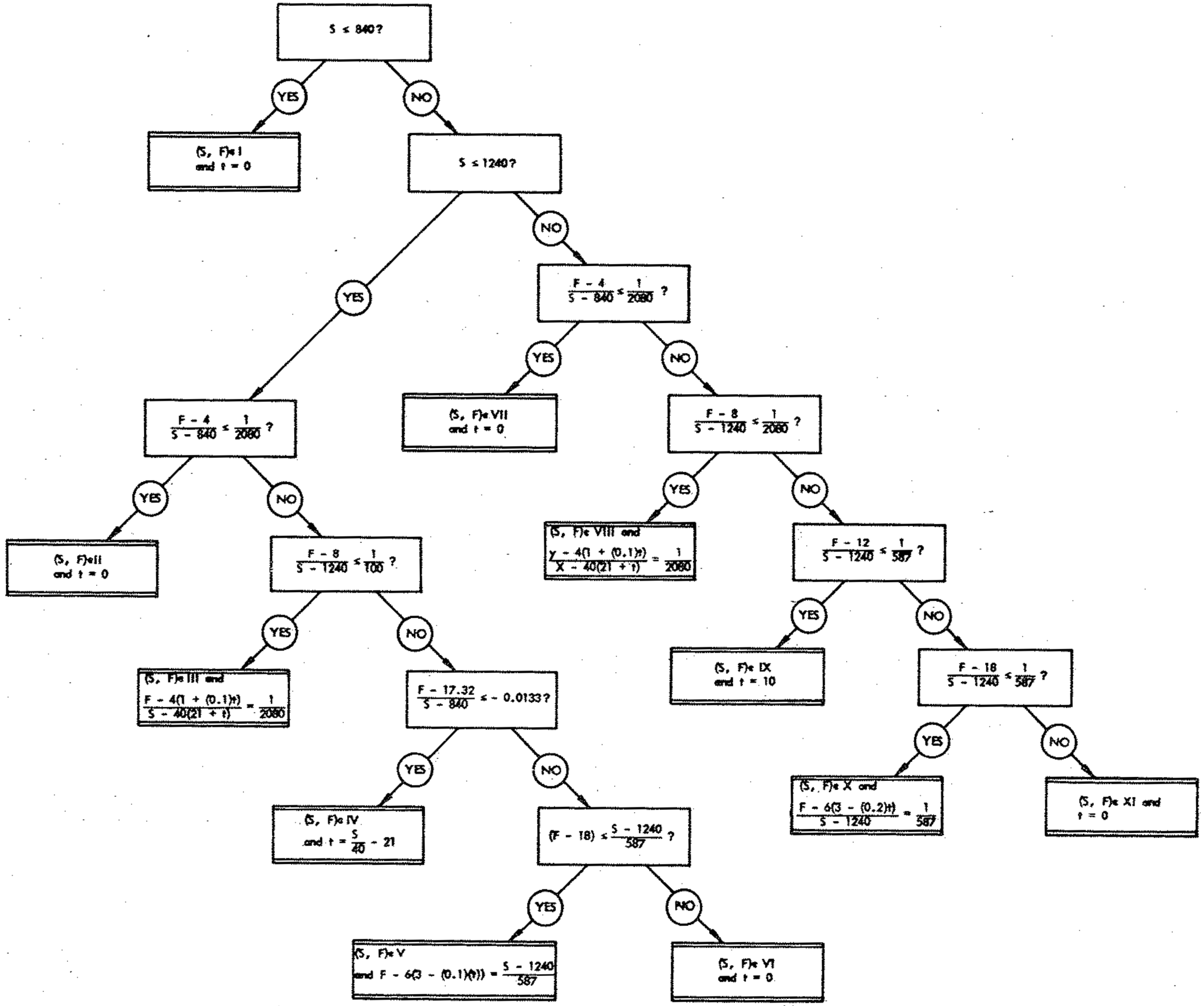

Fig. 15. Algorithmic computation of the (S, F) - score t.

$$\frac{F - 8}{S - 1240} = \frac{1}{100}$$

$$S = 840,$$

$$S = 1240,$$

the (S,F) — score t is given by

$$t = \frac{S}{40} - 21 .$$

(d) In regions III and VIII, with boundaries

$$\frac{F - 8}{S - 1240} = \frac{1}{100}$$

$$\frac{F - 8}{S - 1240} = \frac{1}{2080},$$

$$\frac{F - 4}{S - 840} = \frac{1}{2080},$$

the score t is given by

$$\frac{F - 4((1 + 1.1)(t))}{S - 40(21 + t)} = \frac{1}{2080} .$$

(e) In regions XI, VI, I, II, and VII, $t = 0$.

The effects of the remaining two important factors are given in the usual multiplicative forms, in Figs. 16a and 16b.

The complete rating function $R_1(S, F, v, V)$ is computed as the product $R_1'(S, F, v, V) = [t(S, F)]\left[16^{[A(v) + B(v)]}\right]$, linearly modified to keep the rating away from zero by

$$R_1 = 0.9 \times R_1' + 1 .$$

Again it is of interest to assess how well the rating function is able to simulate actual ratings, and the first 25 mixtures are analyzed as before, in Table 26.

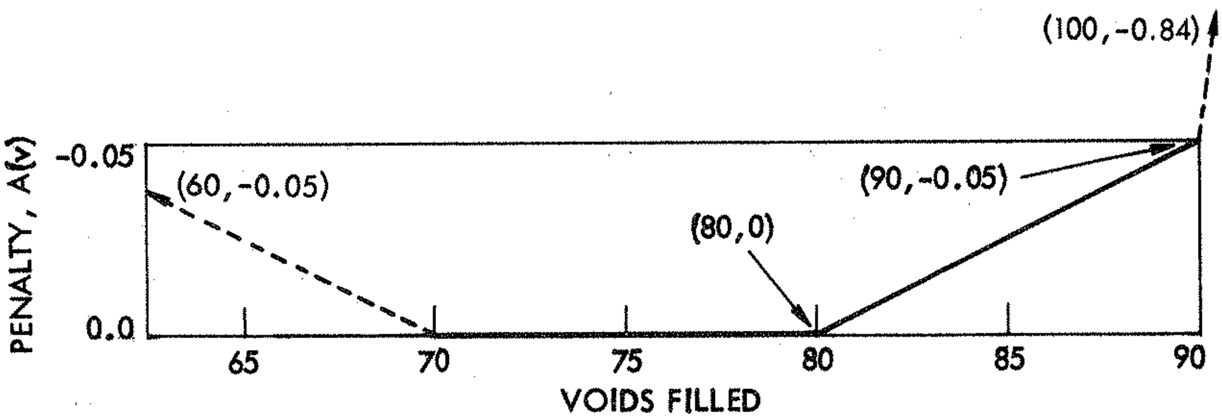

Fig. 16a. Voids filled penalty function A(v), 65 ≤ v ≤ 90.

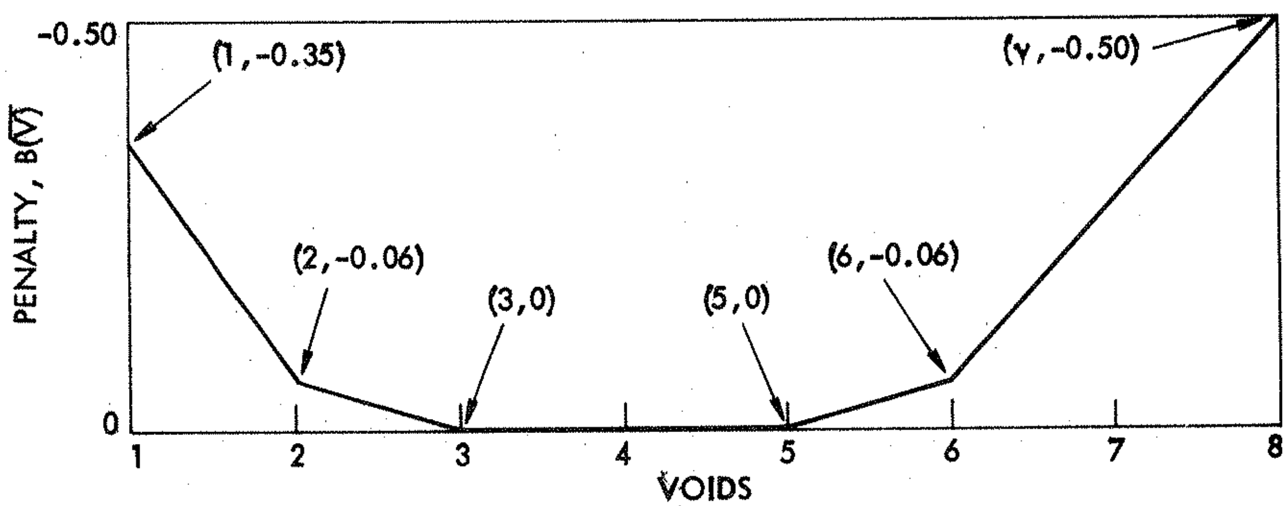

Fig. 16b. Voids penalty function B(v), 1 ≤ V ≤ 8.

Table 26. Comparison between rating function R_1 and actual ratings by Judge K.

Mix No.	Stability, S	Flow, F	t(S,F)	Voids filled, v	Voids, V	A(v)	B(V)	A(v) + B(V)	$16^{A(v) + B(V)}$	$R'_1(S,F,v,V)$	R_1	R
1	3000	16	9.5	90	1	-0.05	-0.35	-0.40	0.33	3	4	2
2	1000	5	3.0	90	1	0.05	-0.35	-0.40	0.33	1	2	2
3	3000	12	10.0	70	3	0.00	0.00	0.00	1.00	10	10	9
4	5000	12	10.0	90	1	-0.05	-0.35	-0.40	0.33	3	4	3
5	500	8	0.0	80	3	0.00	0.00	0.00	1.00	0	1	1
6	5000	16	10.0	90	1	-0.05	-0.35	-0.40	0.33	3	4	2
7	1000	24	0.0	70	1	0.00	-0.35	-0.35	0.38	0	1	1
8	500	24	0.0	90	4	-0.05	0.00	-0.05	0.88	0	1	1
9	5000	8	5.0	70	3	0.00	0.00	0.00	1.00	5	6	8
10	1000	16	1.0	90	2	-0.05	-0.06	-0.11	0.73	1	2	3
11	500	24	0.0	90	3	-0.05	0.00	-0.05	0.88	0	1	1
12	5000	5	0.0	90	8	-0.05	-0.50	-0.55	0.23	0	1	3
13	1000	5	3.0	80	8	0.00	-0.50	-0.50	0.26	1	2	3
14	3000	24	0.0	90	8	-0.05	-0.50	-0.55	0.23	0	1	2
15	3000	12	10.0	80	1	0.00	-0.35	-0.35	0.38	4	4	2
16	3000	16	9.8	90	1	-0.05	-0.35	-0.40	0.33	3	4	2
17	5000	12	10.0	70	4	0.00	0.00	0.00	1.00	10	10	9
18	3000	16	9.5	70	3	0.00	0.00	0.00	1.00	10	10	9
19	1000	12	4.0	80	4	0.00	0.00	0.00	1.00	4	5	3
20	3000	24	0.0	90	3	-0.05	0.00	-0.05	0.88	0	1	2
21	1000	12	4.0	90	1	-0.05	-0.35	-0.40	0.33	1	2	2
22	400	12	0.0	90	8	-0.05	-0.50	-0.55	0.23	0	1	1
23	3000	16	9.5	90	1	-0.05	-0.35	-0.40	-0.33	3	4	2
24	1000	5	3.0	70	2	0.00	-0.06	-0.06	0.85	3	3	3
25	500	24	0.0	90	4	-0.05	0.00	-0.05	0.88	0	1	1

Note that the fit is not quite as good as might have been expected. It is likely that the fit would have been better had a joint penalty function been used, rather than the joint score t.

Section 5. Illustration of the construction of a grand rating function and dispersion function

Construction of a grand rating function will be illustrated for the case J = 2. To the judge analyzed in section IV will be added a judge B whose Marshall ratings are given in Table 27. (Note that the judge

Table 27. Comparison between rating function R_2 and actual ratings of Marshall mixes by Judge B.

Mix No.	S	f(S)	F	g(F)	ν	$a(\nu)$	V	b(V)	VMA	c(VMA)	f(S) + g(F) $a(\nu)$ + b(V)	$R_2(S,F,\nu,V)$	Actual rating
1	3000	-0.05	16	-0.03	90	-0.06	1	-0.30	14	-0.04	-0.48	3	3
2	1000	-0.04	5	-0.30	90	-0.06	1	-0.30	10	-0.25	-0.95	1	1
3	3000	-0.05	12	0.00	70	-0.04	3	0.00	18	0.00	-0.09	8	7
4	5000	-0.15	12	0.00	90	-0.06	1	-0.30	10	-0.25	-0.76	1	2
5	500	-0.15	8	-0.03	80	0.00	3	0.00	10	-0.25	-0.43	3	3
6	5000	-0.15	16	-0.03	90	-0.06	1	-0.30	18	0.00	-0.54	2	3
7	1000	-0.04	24	-0.25	70	-0.04	1	-0.30	14	-0.04	-0.67	2	2
8	500	-0.15	24	-0.25	90	-0.06	4	0.00	18	0.00	-0.46	3	3
9	5000	-0.15	8	-0.03	70	-0.04	3	0.00	10	-0.25	-0.47	3	3
10	1000	-0.04	16	-0.03	90	-0.06	2	-0.15	14	-0.04	-0.32	4	4

involved based his voids assessments independently on the three voids characteristics, lowering his rating in response to undesirable levels of the three.)

The ordinary multiplicative model provided an adequate fit of this judge's ratings and the corresponding derived penalty functions are given graphically in Figs. 17a to 17e. Dashed line portions of these curves were extrapolated by the authors.

The rating function R_2 for this judge is now computed multiplicatively as follows:

$$R_2(S, F, \nu, V) = 10 \times 16^{[f(S) + z(F) + a(\nu) + b(V) + c(VMA(\nu, V))]}$$

To verify the adequacy of this function we compare in Table 27 the first actual ratings with their computed counterparts.

The grand rating function now is computed as the average of $R_1(S, F, \nu, V)$ and $R_2(S, F, \nu, V)$:

$$\bar{R}(S, F, \nu, V) = \frac{R_1(S,F,\nu,V) + R_2(S,F,\nu,V)}{2}$$

For J = 2, the dispersion function reduces to

$$D(S, F, \nu, V) = |R_1(S, F, \nu, V) - R_2(S, F, \nu, V)|/\sqrt{2}$$

Section 6. Grand rating and dispersion for some mixes actually tested.

The rating of mixes using the grand rating function $\bar{R}$ and dispersion function D is now illustrated for four actual mixes in Series B. The Marshall properties at their respective "optimum" asphalt contents determined by standard methods are given in Table 28.

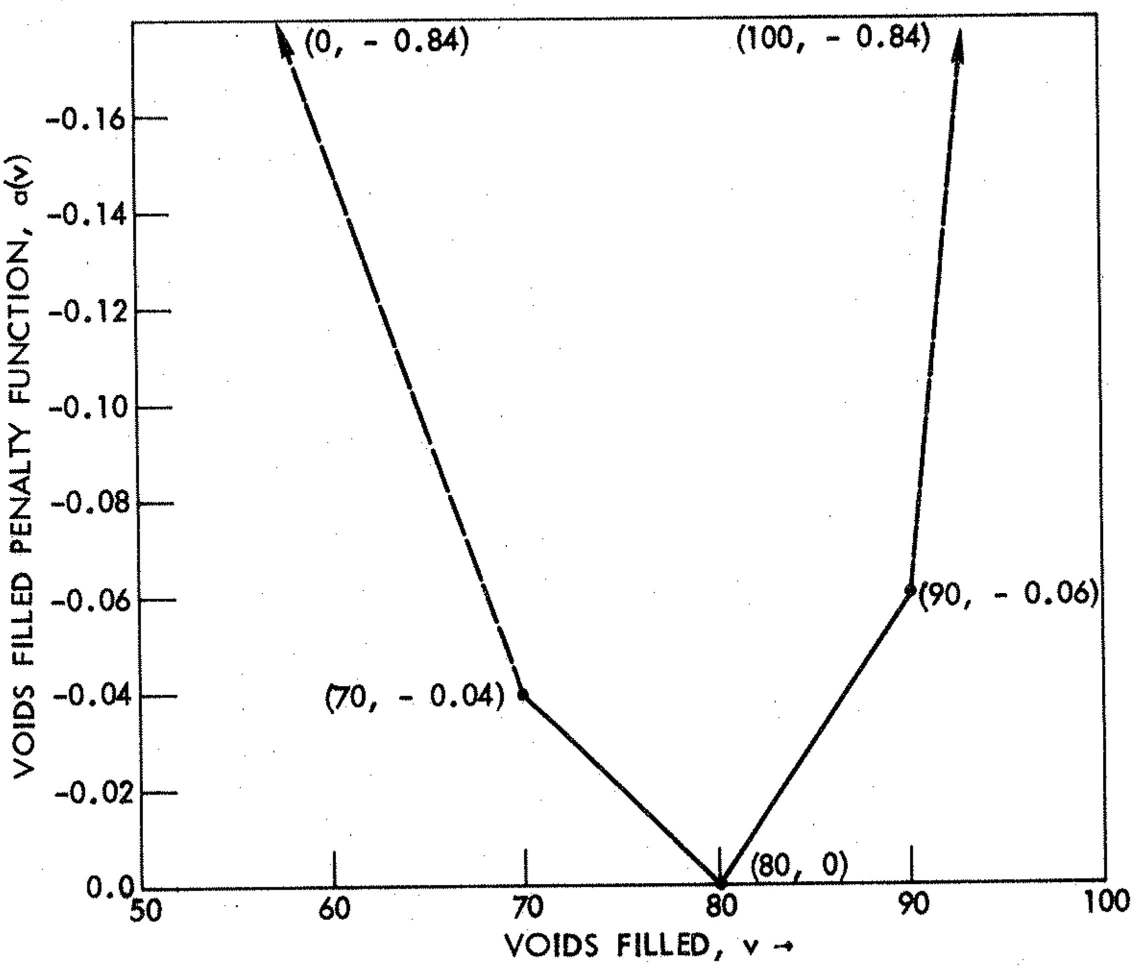

Fig. 17a. Penalty function for voids filled, Judge B.

The rating functions R_1 and R_2 for each mix were first computed using figures and models derived from Judge K and Judge B. The grand rating functions $\bar{R}$ and dispersion functions D for these mixes were then computed as shown in the above section. For comparison, these four functions are tabulated in Table 29, together with rankings of these mixes by four other criteria described previously.

Mix B-091-B095 can be considered a superior mix by any conventional criteria, while Mix B-161-165 was ranked very low by all four Marshall

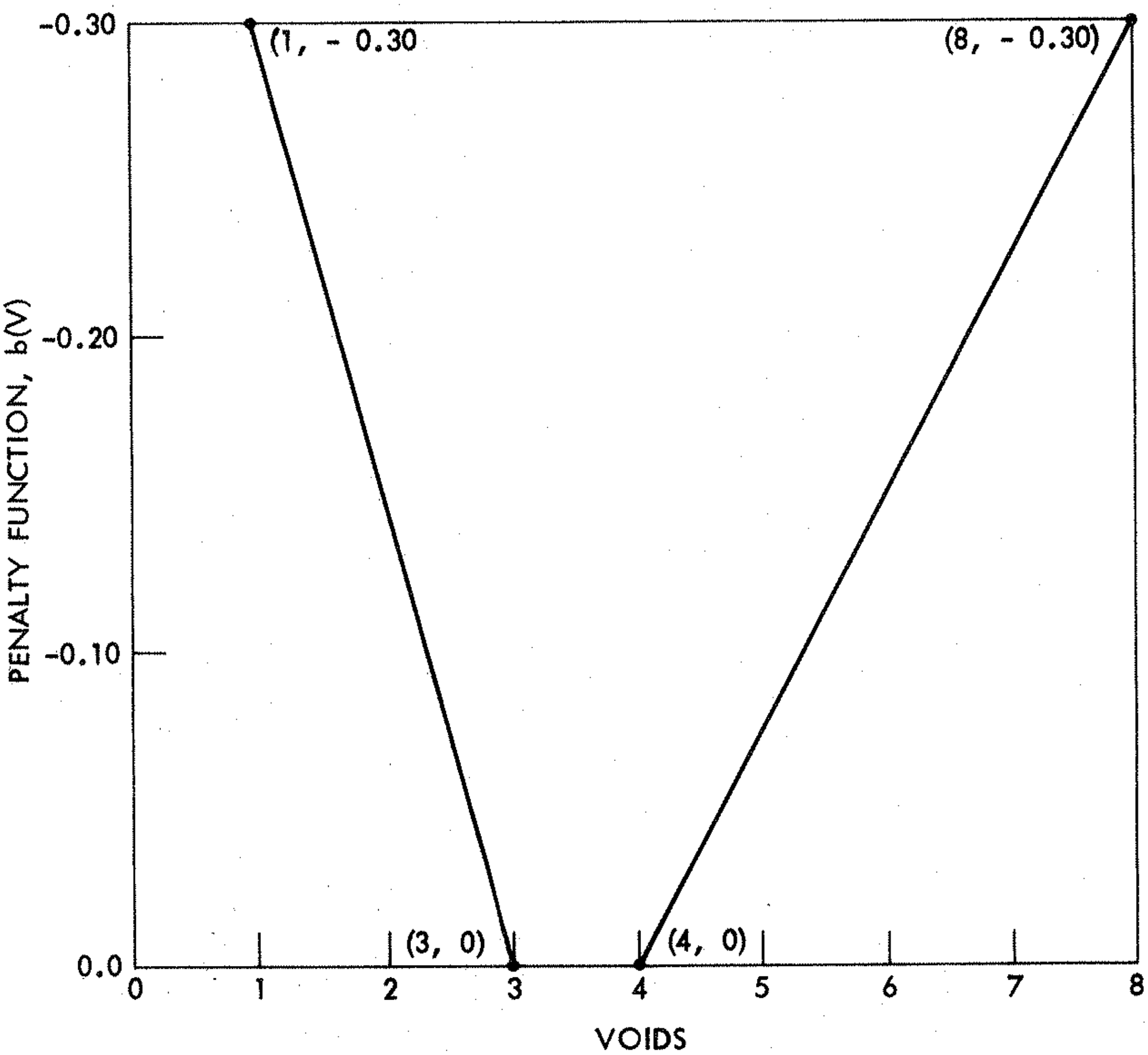

Fig. 17b. Penalty function for air voids, Judge B.

criteria. The other two mixes could be considered satisfactory. Note that, whereas the two separate scores R_1 and R_2 are not entirely in agreement with the rankings by conventional criteria, the average (grand rating) $\bar{R}$ does correlate rather well with these. Presumably, with more judges included in the index $\bar{R}$, a reasonably reliable rating method should result.

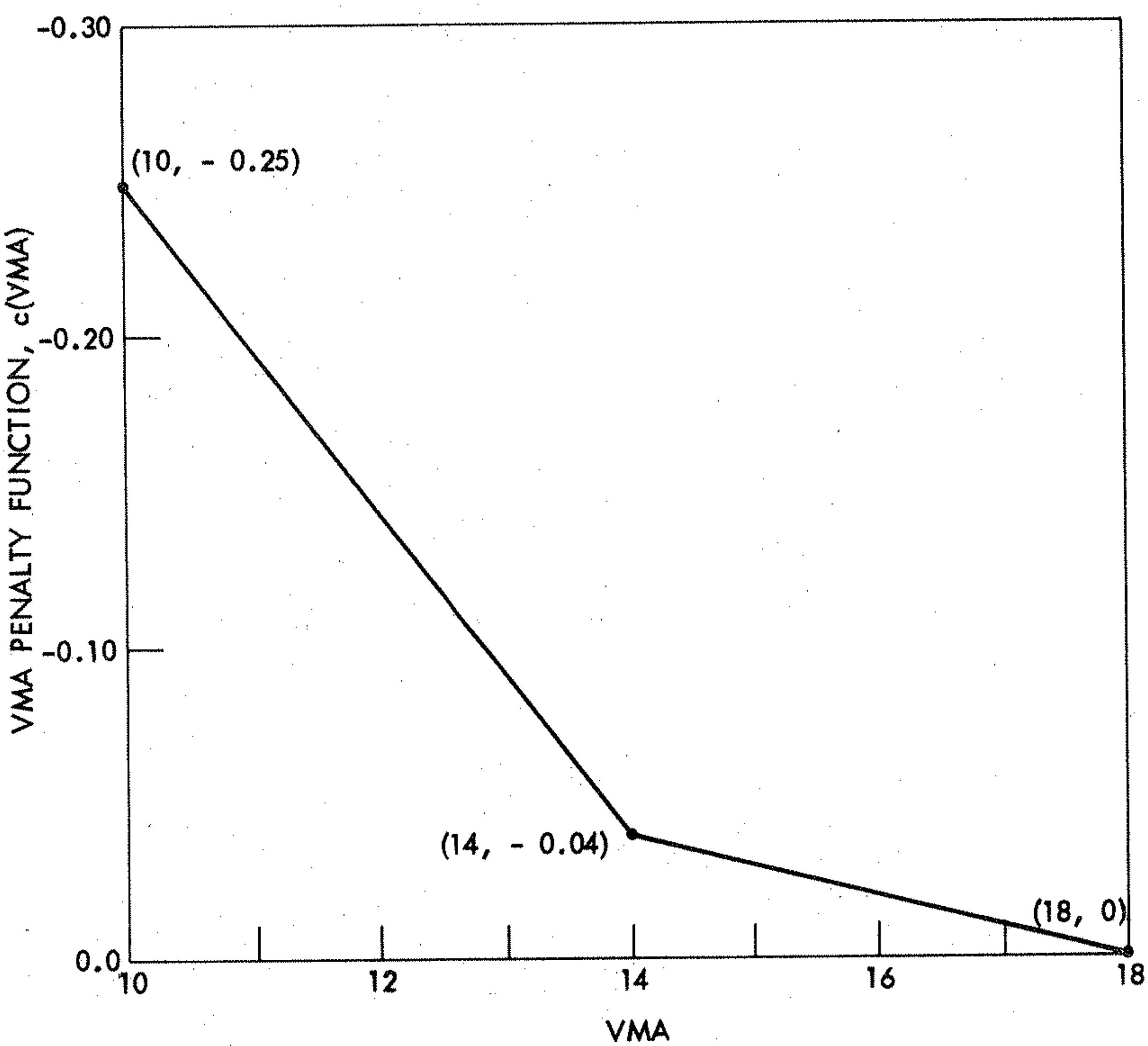

Fig. 17c. Penalty function for VMA, Judge B, 10 ≤ VMA ≤ 18.

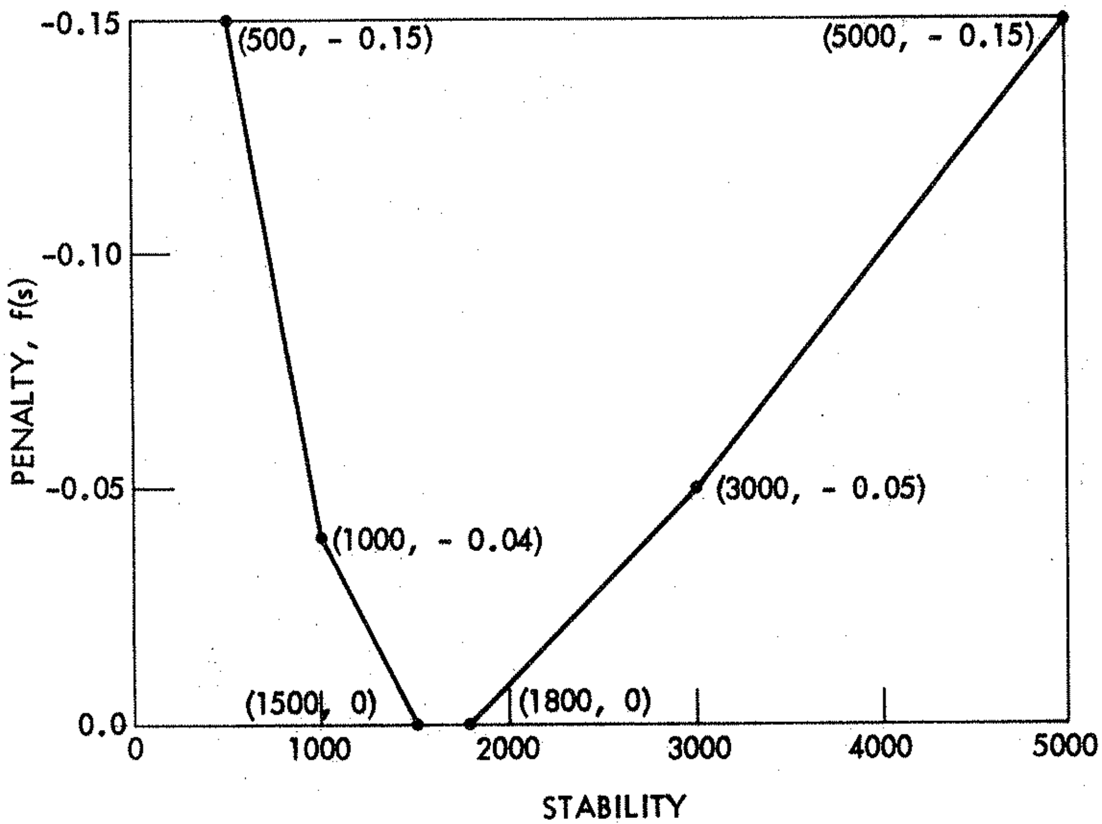

Fig. 17d. Penalty function for stability, Judge B, $500 \leq s \leq 5000$.

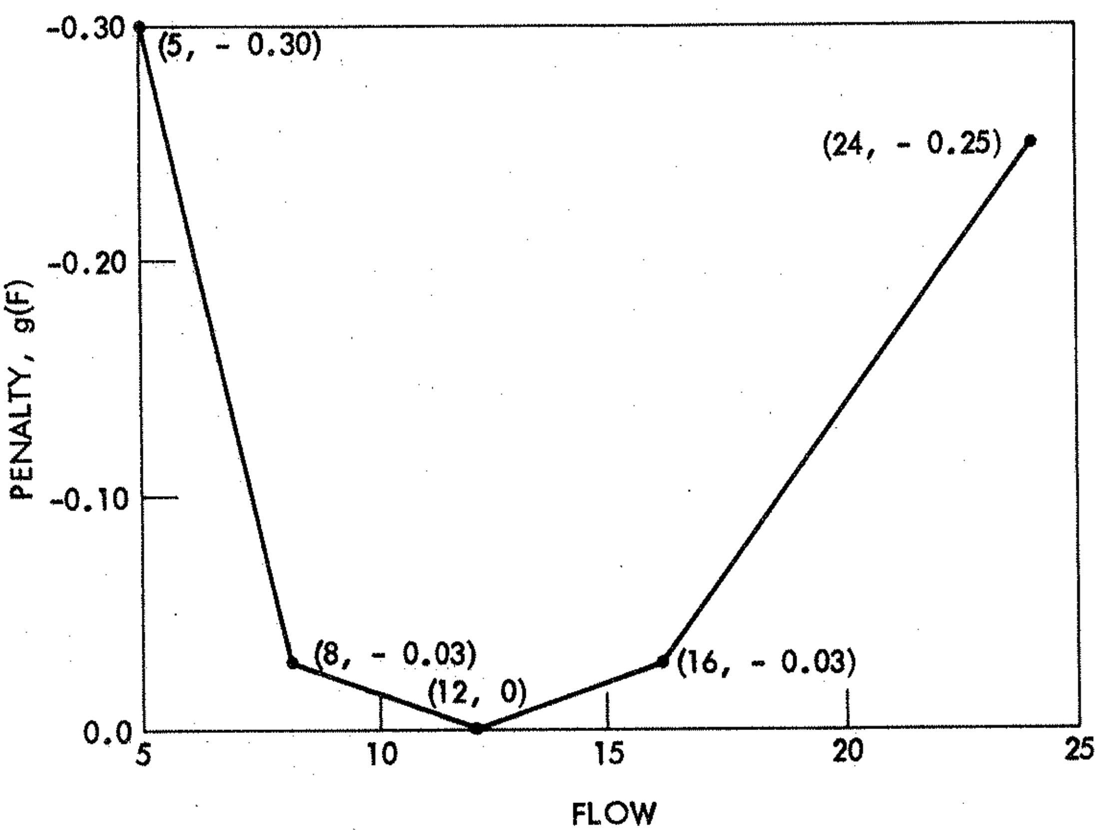

Fig. 17e. Penalty function for flow, Judge B, $5 \leq F \leq 24$.

Table 28. Marshall properties (interpolated) of mixes at optimum asphalt contents.

Mix No.	Optimum asphalt content, %	Air voids, V_a, %	VMA, %	Stability, lb	Flow, 0.01 in.
B001-005	5.6	2.8	11.6	2800	14
B011-015	4.6	3.0	10.8	3240	12
B091-095	5.7	3.5	17.3	3120	12
B161-165	4.7	5.0	11.1	1970	15

Table 29. Comparison between grand rating functions and rankings by other criteria.

Mix No.	R_1	R_2	$\overline{R}$	D	1-A	1-B	1-C	1-D
B001-005	10.0	5.0	7.5	3.5	19	28	19	17
B011-015	10.0	5.0	7.5	3.5	14	9	10	11
B091-095	10.0	8.5	9.3	1.1	2	18	15	14
B161-165	5.0	3.0	4.0	1.4	32	32	32	28

V. SUMMARY AND CONCLUSIONS

1. A comparative laboratory study between well-graded and gap-graded asphalt concrete mixtures was made. A total of 424 batches of asphalt concrete mixtures and nearly 4000 Marshall and Hveem specimens were tested.
2. There is strong evidence that numerous gap-graded or non-well-graded mixtures can be made to meet current design criteria, with proper combinations of aggregate size, type, and asphalt type and asphalt content.
3. Gap gradings A-4L, A-8L, B-30, and C-8L consistently yield mixtures of highest maximum density.
4. The unqualified acceptance of some supposedly desirable constant mathematical relationship between adjacent particle sizes of the form such as Fuller's curve $P = 100(d/D)^n$ is not justified. This investigation demonstrates that both continuous and gap-graded aggregates could produce mixes of high density or low voids. Perhaps surprising, many of these so-called "dense-gradings" gave mixes of some of the lowest maximum densities.
5. <u>All</u> mixes studied, gap or well graded, yielded mixtures with maximum stability far exceeding the minimum of 750 lb required of mixes designed for heavy traffic.
6. The best gaps for high stability mixes appeared to be different for different maximum aggregate sizes and aggregate-asphalt combinations. The well-graded Iowa type A and Federal Highway Administration

gradings (I and P) were usually among the gradings that yielded higher Marshall stability. The best gap gradings for Marshall stability were: A-8, A-30, B-30, B-B, and C-100.

7. Laboratory tests carried out in this investigation have shown that many of the gap-graded mixes possessed strength characteristics such as stability and flow, cohesion, and tensile strength that compare favorably with those of standard mixes of well- or continuously-graded mixes.

8. Allowing acceptance or rejection of aggregates based on individual mix evaluation in lieu of existing "recipe" type specifications or grading limit specifications may lead to more efficient use of local aggregates.

9. For a given gradation, while an optimum asphalt content may exist for maximum density, there may or may not be a unique optimum asphalt content for strength and durability parameters. The current practice of compromising among a number of desirable properties in mix design will most likely continue.

10. Methods of rating or ranking asphalt paving mixtures based on standard Marshall or Hveem properties were suggested. Perhaps most significant and promising were the weighted Marshall stability, the weighted Hveem stability, and the rating functions or quality indices derived from a survey of experts. More work, especially field performance tests, is needed in refining these indices. Potentially, these indices will make it possible for the highway engineers to evaluate and compare asphalt paving mixtures of wide

ranges of aggregate type, size, gradation, asphalt type, and content, based on the established Marshall or Hveem method.

11. Rating, ranking, or the order of merit of specific mix compositions may be quite different by changes in criteria or methods of testing.

12. The gap gradings that resulted in consistently superior mixtures were: A-30, A-8, B-B, B-30, B-100, and C-8. These gradings are recommended for further study, especially on field performances and skid and wear resistance.

13. In order to implement the weighted Marshall stability concept for mixture evaluation and quality control, the stability adjustment factors R_a, R_v, and R_f should be modified and refined by field performance correlation studies.

VI. RECOMMENDATIONS

Engineering and Specification

There is strong evidence from this investigation that both continuous and gap-graded aggregates can produce mixtures of high density and of qualities meeting current design criteria. It is therefore recommended that the aggregate grading limits be relaxed or eliminated and that the suitability (acceptance) or rejection of an aggregate be based on individual mixture evaluation.

Research

Two areas of follow-up research are recommended as a result of work in this investigation:

1. Because of the potential attractiveness of gap-graded asphalt concrete in cost, quality, skid and wear resistance, construction, and construction control, selected gap-graded mixtures should be tested both in the laboratory and in the field, especially in regard to ease of compaction and to skid and wear resistance.

2. Perhaps equally important and significant is the development of a quality index for rating and evaluating asphalt paving mixtures based on standard Marshall or Hveem method, whose use is currently limited only to asphalt content determination. These indices will make it highly possible for the highway engineers to design and evaluate asphalt paving mixtures of wide ranges of aggregate size, grading, and type, asphalt type, and content. It is therefore recommended that field performance tests and correlations be conducted to refine and modify the developed rating functions and quality indices based on Marshall properties.

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