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Final Report

TREATING IOWA'S MARGINAL AGGREGATES AND SOILS BY FOAMIX PROCESS

Laboratory Study

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1. INTRODUCTION

1.1. Background

Quality granular materials suitable for building all-weather roads are not uniformly distributed throughout the state of Iowa. For this reason the Iowa Highway Research Board has sponsored a number of research programs for the purpose of developing new and effective methods for making use of whatever materials are locally available. This need is ever more pressing today due to the decreasing availability of road funds and quality materials, and the increasing costs of energy and all types of binder materials.

In the 1950s, Professor L. H. Csanyi (8-12) of Iowa State University had demonstrated both in the laboratory and in the field, in Iowa and in a number of foreign countries, the effectiveness of preparing low cost mixes by stabilizing ungraded local aggregates such as gravel, sand and loess with asphalt cements using the foamed asphalt process. In this process controlled foam was produced by introducing saturated steam at about 40 psi into heated asphalt cement at about 25 psi through a specially designed and properly adjusted nozzle. The reduced viscosity and the increased volume and surface energy in the foamed asphalt allowed intimate coating and mixing of cold, wet aggregates or soils. Through the use of asphalt cements in a foamed state, materials normally considered unsuitable could be used in the preparation of mixes for stabilized bases and surfaces for low traffic road construction. By attaching the desired number of foam nozzles, the foamed asphalt can be used in conjunction with any type of mixing plant, either stationary or mobile, batch or continuous, central plant or in-place soil stabilization.

The extensive laboratory and field tests conducted at Iowa State University disclosed a number of advantages of the foamed asphalt process, including the following:

- Ungraded local aggregates may be used in producing satisfactory mixes for paving purposes.
- Cold, damp or wet aggregates may be used in the production of cold mix asphaltic concretes.
- Clayey, sandy or granular soils may be stabilized in a moist condition with asphalt cements by either stationary plants or mobile road mix plants.
- Asphalt concrete mixes can be stockpiled for long periods of time.

1.2. Foamix

In 1968, the patent rights for the Csanyi process were acquired by Mobil of Australia. By 1970 Mobil had modified the process for foaming by replacing the steam with 1-2% cold water and further allowing mixing of the foam through a suitable mixing chamber (3-7). Mobil was granted a patent in Australia in 1971 and the patent has now been extended to at least 14 countries; some type of work related to foamed asphalt is being performed in at least 16 countries (23). In the U.S., Conoco, Inc., has the rights to the foam process.

The basic Mobil foaming process consists of introducing cold water under controlled flow and pressure into hot asphalt cement in a specially designed foaming chamber which discharges the foamed asphalt into the cold, moist aggregate through the nozzles of a spray bar. The Mobil foamed asphalt process (Foamix) has been adapted to continuous mix plants, drum mixers and batch plants. The process has also been used in travel plants for processing in-situ material for soil stabilization work. The Colorado Department of Highways has been evaluating the Foamix process, with FHWA participation on an HPR research project (1). Other highway agencies that are experimenting with this process include Indiana, Michigan, Texas, North Dakota and Oklahoma.

Although many miles of foamed asphalt mixtures have been produced by the Csanyi process for surface construction, the foamed asphalt mixtures produced by the Mobil process have been mainly used for base and subbase construction.

1.3. Advantages of the Foamix Process

Based on experiments conducted in Australia, South Africa and Colorado, Foamix appears to have the following economic, applicational and environmental advantages:

- Cold mix base course can be produced with cold, wet and marginal aggregates including sand and gravel.
- Conventional equipment can be used in continuous plants, for in-situ mixing, and in drum dryer mixers with minimum modification.
- No aeration or curing is required before compaction.
- Less energy consumption compared with Csanyi process (no saturated steam required).
- Use of 100% asphalt cement instead of 60% as is the case with emulsion.

- Minimum problems with dust, diluent fumes or blue smoke when used in asphalt recycling.

In view of these potential advantages of the foamed asphalt process and the need for effective means of producing low cost pavement mixtures with locally available materials, this research was initiated.

2. OBJECTIVES

It was envisioned that the research on foamed asphalt would be conducted in two phases. Phase 1 consists of laboratory evaluation of marginal materials and Phase 2 will be one or more field trials to gain experiences associated with foamed asphalt construction, control, performance and to establish mix design criteria suitable for Iowa conditions.

The objectives of Phase 1 research were to investigate, in the laboratory with a Mobil/Conoco Foaming Unit, the suitability of:

1. Representative marginal but locally available Iowa aggregates and soils as foamed asphalt stabilized base courses,
2. Cold mix recycling by foamed asphalt process, and
3. Stabilizing materials present on country roads (gravels and rocks) by the foamed asphalt process.

3. METHODS OF INVESTIGATION

3.1. Materials

3.1.1. Soils and Aggregates

As orginally proposed, four local materials (a gravel, a sand, a loess and a limestone crusher waste) were to be evaluated in conjunction with an asphalt cement. As a result of a meeting on November 2, 1979, it was decided that five local materials would be studied in conjunction with two asphalt cements. However, six materials (about 300 lb each) were delivered to Iowa State University during November and December, 1979. To some degree, all six materials were evaluated. They were: a plastic loess (B-1) from north of Earling, Shelby Co.; a pit run sand (B-2) from Corely Gravel Pit, south of Harlan, Shelby Co.; a blow sand (B-3) from Poweshiek Co.; a pit-run gravel (B-4) from Peterson Pit, Story Co.; a limestone crusher waste (B-5) from South Waterloo Quarry, Black Hawk Co.; and a second blow sand (B-6) from south of Harlan, Shelby Co. Loess (B-1) was further blended with pit run sand at 20/80, 30/70 and 40/60 ratios making B-8, B-9 and B-10; blended with Shelby Co. blow sand (B-6) at 10/90 ratio making B-7; and blended with Poweshiek Co. blow sand (B-3) at 20/80 ratio making aggregate B-11. All told, eleven aggregates and aggregate blends were studied. In addition, two existing county road surface (top 4 to 6 in.) materials were obtained. One was from Mortensen Road, south of Ames, Story Co. (C-1) and one was from the southeast corner of Shelby Co. (Secs. 21, 28 and 33 Clay Twp.), designated as C-2.

To evaluate the feasibility of cold recycling using foamed asphalt, a reclaimed material from the Kossuth Co. 1979 recycling project (LP-138-

73-55) and a salvaged crushed bituminous pavement from the I-80 Stuart stockpile were obtained together with virgin aggregates used in the respective projects.

3.1.2. Asphalt Cements

Two asphalt cements, an AC-10 and a 200/300 pen. grade, provided by Koch Refinery, Algona, were used in the study.

3.2. Program of Testing

In order to evaluate the foamed asphalt mixtures for a range of material combinations using different compaction and testing methods under different conditions, and to obtain results that can be used to compare with Professor Csanyi's work, the following series of experiments were conducted.

3.2.1. A Series (AC-10):

In this series 12 aggregate and aggregate blends were combined with foamed asphalt AC-10 at ranges of asphalt contents. Standard Marshall specimens were molded and tested for stability, flow, voids, and 24 hr immersion stability. Hubbard-Field properties were evaluated on the six fine material combinations at about 4% foamed asphalt content. Hveem specimens for the nine major aggregates at about 4% foamed asphalt content were compacted by kneading compactor and tested for Hveem stability. The same nine foamed asphalt mixes were also tested for c, ϕ and deformation modulus using the recently developed Iowa K-test device (15). To compare with hot mixes and emulsion mixes, Marshall specimens were prepared and tested at 4% asphalt content of hot mixes using AC-10 and at 4% residue content of emulsion mixes using CSS-1h.

3.2.2. P Series (200/300 pen.)

In this series six aggregates and aggregate blends were mixed with foamed asphalt using 200/300 pen. asphalt cement at ranges of asphalt contents. Marshall specimens were molded, cured and tested for stability, flow and voids properties. Hot mixes were made using selected aggregates at 4% asphalt and tested for Marshall properties.

3.2.3. Special Studies

Several series of foamed mixes were made on selected aggregate-asphalt combinations to evaluate properties relevant to the use of foamed asphalt as base material but not included in conventional asphalt mix design, and to evaluate factors considered important to foamed asphalt production and control.

(1) Effect of Mixing Moisture Content: Foamed asphalt mixes at about 4% were prepared at ranges of prewet mixing moisture content from near zero to 100% of optimum moisture content by AASHTO T99 on four aggregates using 200/300 pen asphalt. Standard Marshall properties were determined.

(2) Effect of Curing Conditions: Foamed mixes were prepared at about 4% asphalt content using B-3 blow sand. Marshall specimens were prepared and tested after being cured at two different temperatures, both in and out of molds, for different periods of time and tested for cured moisture content and Marshall stability-voids properties.

(3) Effect of Foam Half-Life and Foam Ratio: Foamed mixes were prepared at about 4% asphalt cement 200/300 pen using B-3 blow sand.

Foam half-life was varied from 11 to 136 sec and foam ratio was varied from 5 to 20. Standard Marshall specimens were molded, cured and tested for standard stability and voids, 24 hr immersion (at 140°F) stability and absorption.

(4) CBR of Foamed Mixes: Foamed asphalt mixes at 0 and 4% asphalt were prepared at several mixing moisture contents and compacted to standard proctor density and cured at 140°F in molds for 0, 3 and 7 days. CBR and swell were determined.

(5) Freezing and Thawing Resistance of Foamed Mixes: Paired hot and foamed mixes using C-1, B-6 and B-8 aggregates at 4% asphalt were prepared. Marshall specimens were molded and cured (in the case of foamed mixes). The specimens were then subjected to ASTM C666 Freezing in Air - Thawing in Water cycles. The specimens were removed from the freezing-thawing chamber and tested for retained Marshall stability.

(6) Effect of Lime and Portland Cement Treatments of Foamed Mixes: Because of relatively low Marshall immersion (25 hr at 140°F) stability from data obtained during the earlier part of this project, a series of foamed mixes was prepared in which aggregates (B-4 and B-7) were treated with 2% of hydrated lime and and portland cement. Marshall specimens were molded, cured and tested for immersion stability for possible improvement due to these treatments.

(7) Cold Mix Recycling: Two salvaged asphalt pavement materials were blended with desired percents of virgin aggregates. Foamed

mixes were prepared at ranges of moisture and asphalt content and compared with hot recycled mixtures in terms of Marshall properties.

3.3. Methods and Procedures

3.3.1. Aggregates and Soils

Aggregates and soils of the eight basic materials were tested for gradation, Atterberg limits, specific gravity and maximum density and optimum moisture content according to Standard AASHTO T99 procedure.

3.3.2. Asphalt Cements

Asphalt cements were tested for penetration, specific gravity and viscosity at 140°F and 275°F.

3.3.3. Foamed Asphalt Production:

Foamed asphalt was produced by a foaming unit built by Conoco, Inc. and loaned to Iowa State Univesity. Foaming conditions were adjusted to produce a foamed asphalt with a foam ratio (ratio of the volume of the produced foam to the volume of the unfoamed asphalt) of 10-15 and a half-life (time needed for the foam to collapse to half of its original volume) of 26-40 sec determined in a one-gallon can. For the two asphalt cements used in the study, the following foaming conditions were found necessary for the desired foam quality:

- asphalt temperature: 315 to 325°F
- water pressure: 45 psi
- foaming water content: 1.5 to 2.0% by volume of asphalt

- air pressure: 26 psi
- anti-foam counter agent AN480: 0.4 to 0.7% by wt. of asphalt

3.3.4. Foamed Mix Preparation

Three to five batches of foamed asphalt mixes were prepared for each aggregate (or soil aggregate blend) and asphalt cement combinations at a range of asphalt content (3-6%) after the moisture content of aggregate was adjusted to about 70% of optimum moisture content as determined by AASHTO T99. The mixes, 3500-5000 g per batch, were prepared in a 1/3 cu ft mixing bowl in a C100 Hobart planetary mixer. The moist aggregate at room temperature was mixed while the foamed asphalt was being introduced. Mixing was accomplished by mechanical mixing for two minutes followed by hand mixing for one minute. The required asphalt was added through a calibrated timer. The actual asphalt content in the mix was determined by weight difference of the mixing bowl plus content before and after asphalt addition. Moisture content sample of the mix was taken immediately after mixing. The test specimens (Marshall, Hveem, Hubbard-Field, CBR, Iowa K-test, etc.) were molded either following mixing or the following day. In the latter case, the mix was sealed with Saran Wrap and aluminum foil to prevent loss of moisture. Except for series cured under special conditions, all specimens were compacted at room temperature, extruded from the molds and cured at 140°F for three days before tests were performed.

3.3.5. Sample Compaction and Testing

Marshall specimens for all foamed mixes were compacted and tested following ASTM D1559 except that a mechanical compactor was used to compact 50 blows per side at room temperature and foamed mixes were tested after three-days' curing at 140°F using an automatic recording Marshall tester. Marshall *immersion tests* were performed on some series after the cured specimens were immersed in water at 140°F for 24 hrs.

Hubbard-Field foam mix specimens of 2 in. in diamter by 1 in. high were compacted at room temperature and cured, then tested at 77°F dry, after one hour in an oven at 140°F and after one hour in water at 140°F following The Asphalt Institute procedure (2).

Hveem specimens in all foamed mixes were compacted at room temperature using a kneading compactor, cured and tested at 140°F following ASTM D1561 and D1560, except that cohesion was not determined.

CBR tests for foamed mixes were performed on specimens molded according to standard AASHTO T99 compaction effort (five layers, 12 blows per layer using a 10 lb hammer) and after specimens were cured at 140°F while in the mold.

The Iowa *K-test* was performed on foamed mixes compacted at room temperature to standard Proctor sample size of 0.03 cu ft following AASHTO T99 compaction, cured at 140°F for three days, and tested at room temperature according to the procedure described by Handy et al. (15). In this test the specimens were subjected to vertical compression at a rate of 0.05 in. per min while confined in a split steel mold the size of the standard Proctor specimen. The mold acts as a spring, providing a continuous measure of lateral stress. From a p-q plot, undrained ϕ and c can be obtained by means of least squares regression analysis from a single sample.

4. RESULTS AND DISCUSSION

Thirteen aggregates and aggregate blends plus two recycled asphalt pavement materials were evaluated in conjunction with two asphalt cements for foamed asphalt mixes. These were compared with hot mixes and emulsion mixes at selected material combinations and asphalt contents. In all more than 500 specimens were tested from approximately 150 batches of mixes. In the following sections, the results of these tests will be discussed.

4.1. Material Characteristics

The gradation, Atterberg limits, specific gravity, AASHTO T99 density and optimum moisture content and AASHTO soil classification of the eight major aggregates are given in Table 1. They ranged from non-plastic A-1-b (B-2) to plastic loess A-7-6 (B-1). The gradation curves of these aggregates are shown in Figs. 1-5. The physical properties of the two asphalt cements are given in Table 2.

4.2. Foamed Mixes - Series A (AC-10)

More than 40 batches of foamed mixes were made using 12 aggregates and aggregate blends for Marshall specimens at ranges of asphalt content. Additional batches at approximately 4% asphalt were made for the nine major aggregates for Hubbard-Field, Hveem and Iowa K-tests.

The general appearance and characteristics of foam and foamed asphalt stabilized cold mixes using the water/air foaming unit were not

Table 1. Physical Properties of Soil Aggregates

No.	B-1	B-2	B-3	B-4	B-5	B-6	C-1	C-2
Material	Loess	Pit-run Sand	Blow Sand	Pit-run Gravel	Limestone Waste	Blow Sand	Crushed Stone	Crushed Stone
AASHTO Classification	A-7-6	A-1-b	A-2-4	A-1-b	A-2-4	A-3	A-6	A-2-6
Source	Shelby Co.	Shelby Co.	Poweshiek Co.	Story Co.	Black Hawk Co.	Shelby Co.	Story Co. Road	Shelby Co. Road
Gradation				% Passing				
Sieve Size								
1 in	100	100	100	100	100	100	100	100
1/2 in	100	97	100	92	100	100	97	87
3/8	100	94	100	81	100	100	95	78
4	100	89	100	69	99	100	88	62
8	100	87	100	60	92	100	83	53
16	100	66	100	48	64	98	78	44
30	100	53	99	38	51	94	72	36
50	100	21	74	21	40	58	65	32
100	100	6	24	14	33	5	51	28
200	99	5	12	12	29	1	44	23
5 μ	15						18	7
2 μ	11						15	5
L.L.	46.6				15.8		34.0	30.3
P.L.	16.2				14.5		20.3	11.1
P.I.	30.4	N.P.	N.P.	N.P.	1.3	N.P.	13.7	19.2
Specific Gravity, Bulk	--	2.628	2.618	2.585	2.650	2.621	2.577	2.563
Apparent	2.714	2.689	2.666	2.877	2.782	2.663	2.642	2.697
Standard Proctor Dry Density, pcf	102.8	118.8	114.3	137.1	126.8	106.3	113.5	128.8
Optimum Moisture Content, %	19.6	10.8	12.5	8.2	12.1	15.7	15.1	8.8

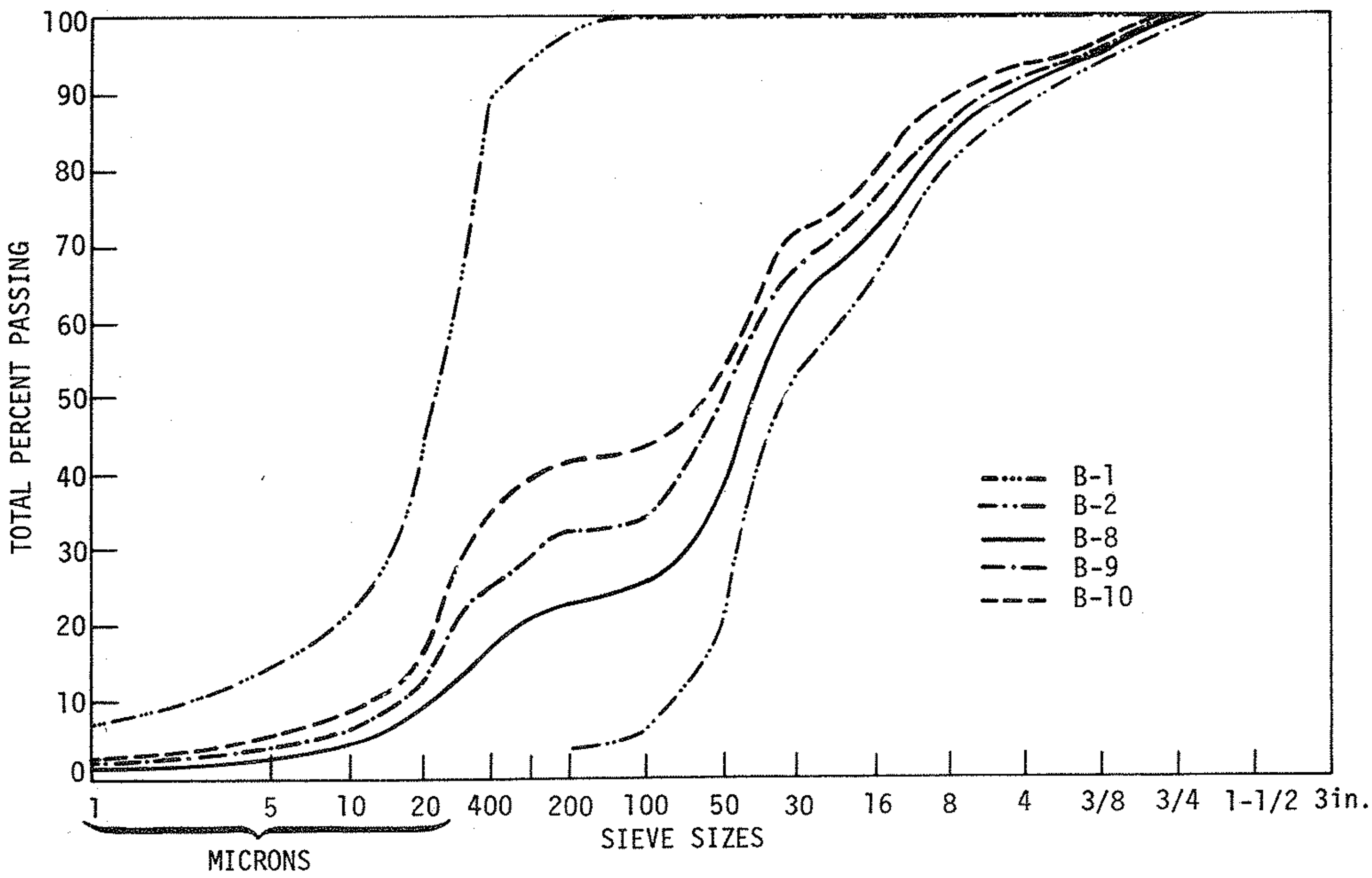

Figure 1. Gradation of aggregates B-1, B-2 and their blends (B-8, B-9, B-10).

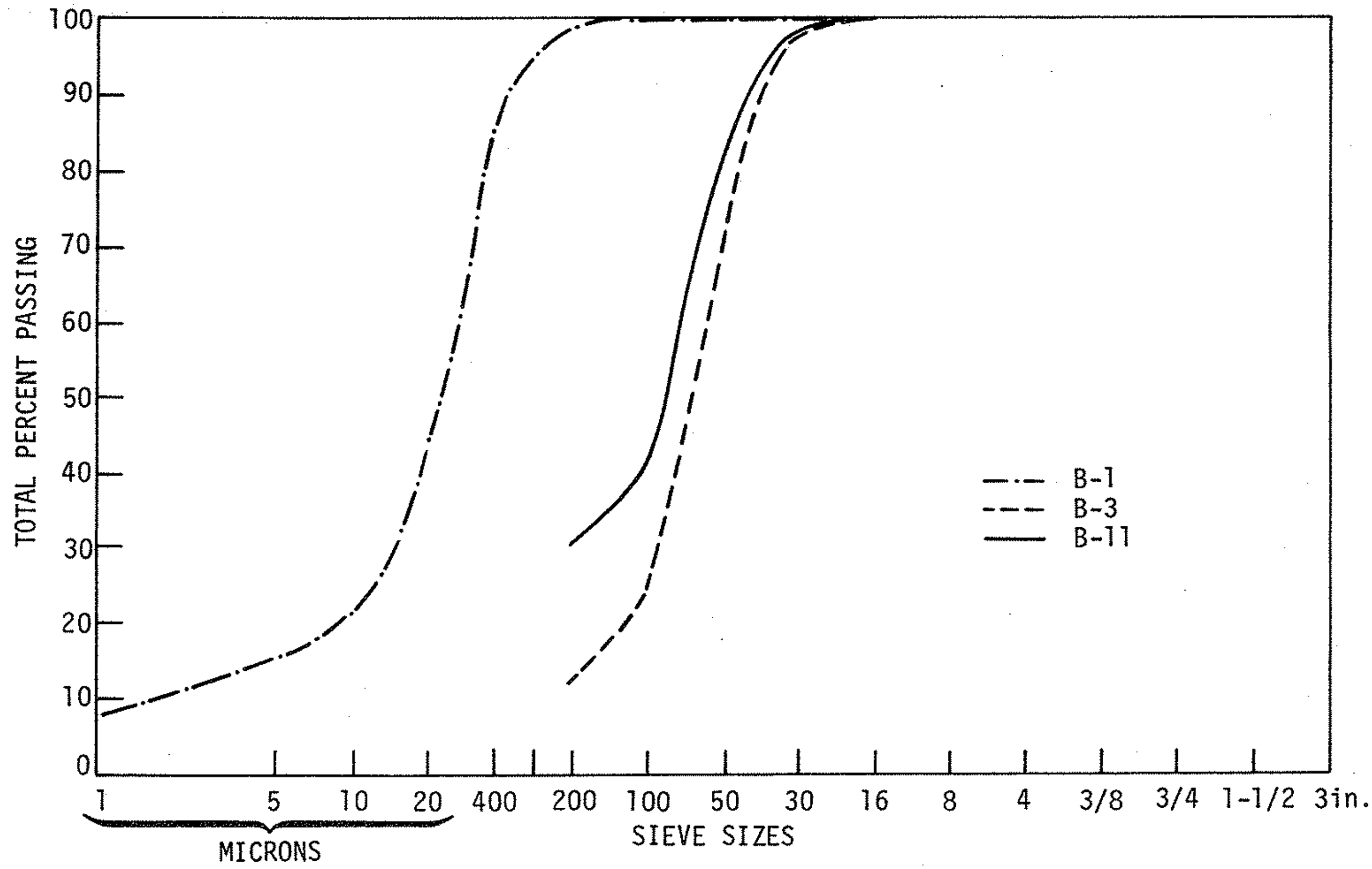

Figure 2. Gradation of aggregates B-1, B-3 and their blend B-11.

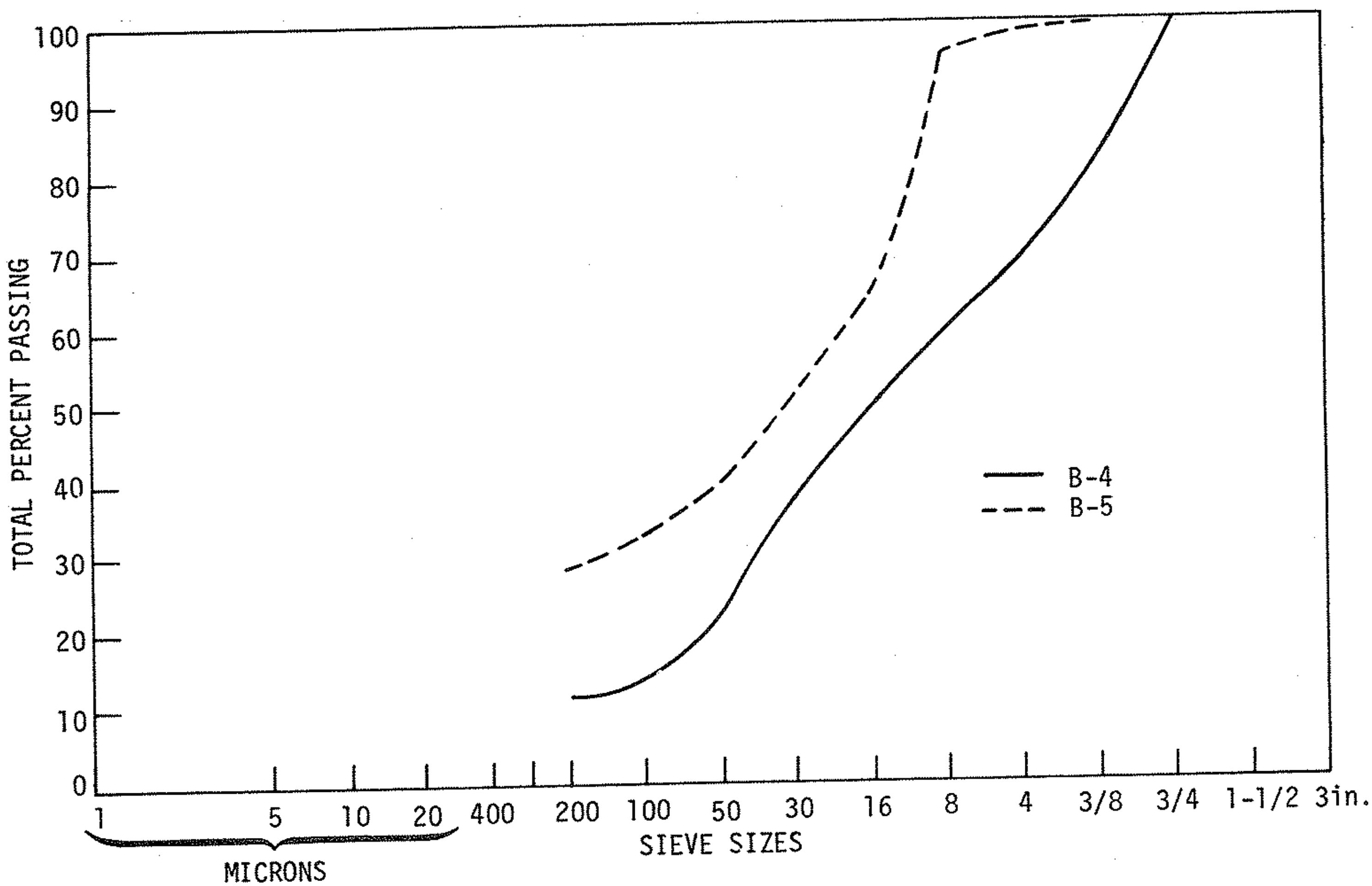

Figure 3. Gradation of aggregates B-4 and B-5.

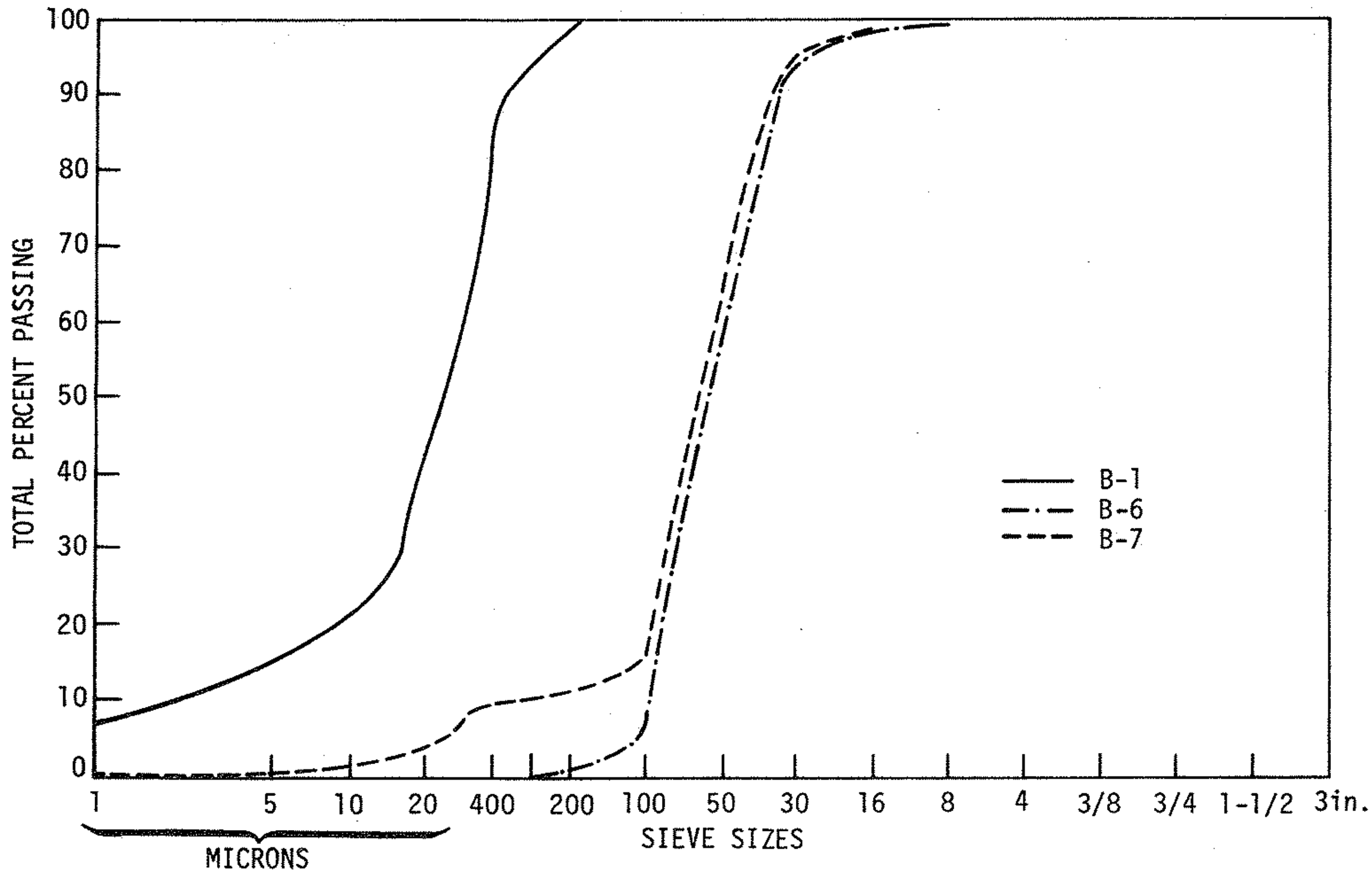

Figure 4. Gradation of aggregates B-1, B-6 and their blend B-7.

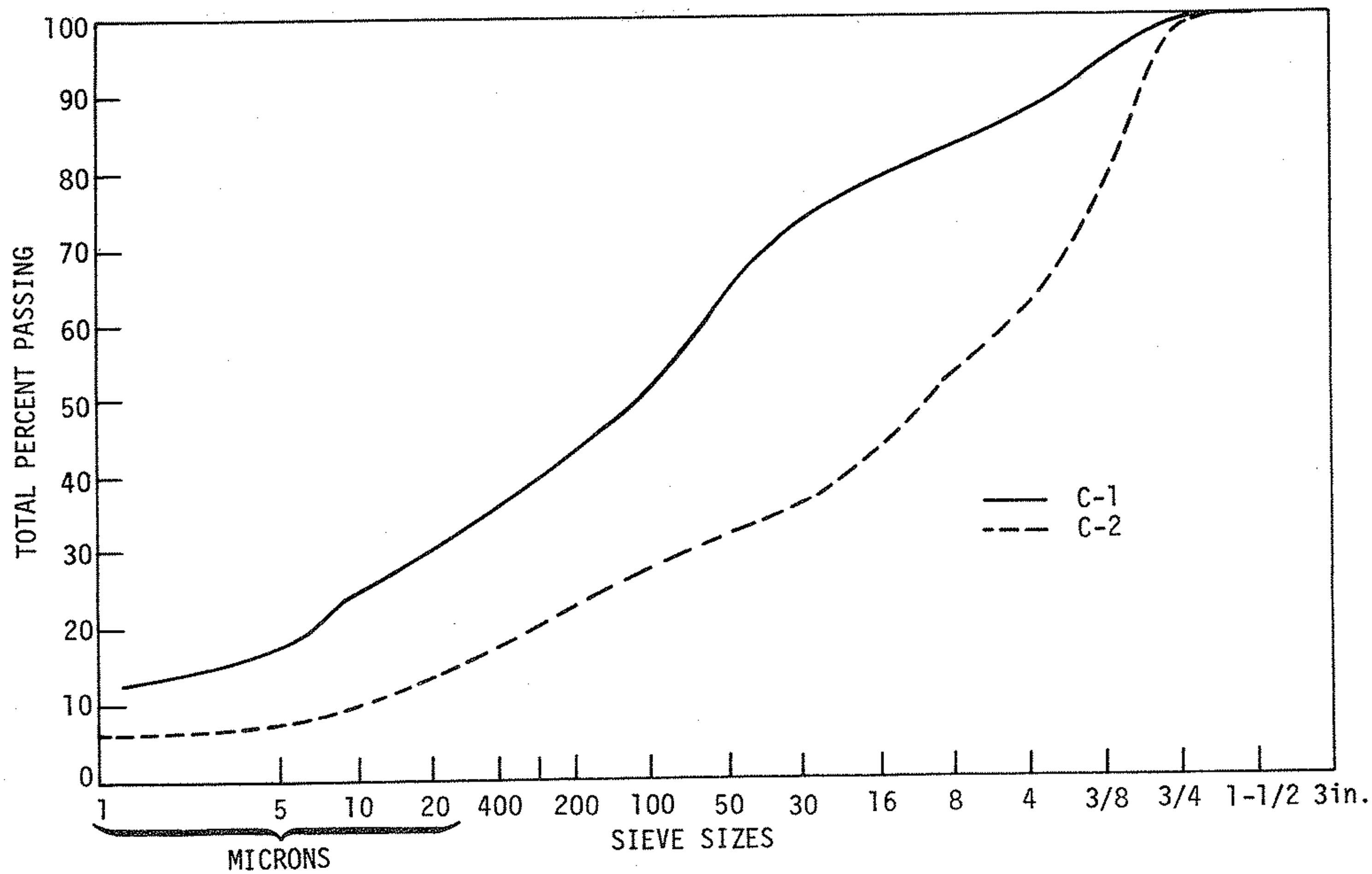

Figure 5. Gradation of road surface materials C-1 and C-2.

Table 2. Properties of Asphalt Cements

A.C. Grade	200-300 pen. (p)	A.C. 10 (A)
Penetration @ 77°F	217	84
Viscosity @		
140°F, p.	413	1556
275°F, cs	173	320
Sp. Gr.	1.001	1.026

unlike that produced by Csanyi's steam foaming process, except that there was no record to suggest that Professor Csanyi had encountered any asphalt cement that could not be foamed by proper selection and adjustment of nozzle and at proper steam and asphalt pressures. Some of the salient features of foamed mixes produced by either process are:

- Some moisture content (50-100% of optimum by AASHTO T99) is required in the aggregate before the addition of foamed asphalt for uniform distribution of asphalt and coating of the aggregate/soil particles.
- Large aggregate particles over 1/4 in. are seldom coated.
- Foamed asphalt cold mixes right after asphalt addition are light in color with no visible asphalt, not unlike clean, moist aggregates. However, a few minutes after mixing and compaction the mixes darken and within a few days all fine particles are coated.

Test results for foamed mixes using AC-10 asphalt cement and Marshall procedures are given in Table 3. The results of Hveem, Hubbard-Field and Iowa K-Tests of foamed mixes at approximately 4% AC-10 are given in Table 4. The mixes were all prepared at ambient temperatures. The mixing and compaction moisture contents were approximately 70% of optimum moisture content determined by AASHTO T99. Several features are common to all foamed mixes of a given soil aggregate:

- There is an optimum foamed asphalt content for stability.
- There is an optimum asphalt content for compacted bulk specific gravity (unit weight).

Table 3. Marshall Properties of Foamed Asphalt Mixtures - Series A (AC-10)

Aggregate	B-1					B-2				B-3				B-4				B-5			
Material	Loess					Pit-run sand				Fine sand				Pit-run gravel				Crusher waste			
Mix No.	FA4B1	FA5B1	FA6B1	FA7B1	FA9B1	FA3B2	FA4B2	FA5B2	FA6B2	FA3B3	FA4B3	FA5B3	FA6B3	FA3B4	FA4B4	FA5B4	FA6B4	FA4B5	FA5B5	FA6B5	FA7B5
Asphalt Content, %	4.4	5.5	6.8	7.3	9.5	2.7	3.7	4.5	5.2	3.0	4.3	5.6	5.8	3.0	4.3	5.0	5.7	4.1	4.8	6.0	6.9
Mixing m.c., %	14.7	14.7	14.7	14.7	9.8	7.1	7.1	7.1	7.1	9.4	9.4	9.4	9.4	6.2	6.2	6.2	6.2	7.7	6.9	6.5	7.7
Cured m.c., %	4.2		1.8		2.4	--	1.0	--	0.1	1.0	0.8	1.1	0.7		0.8			1.0	0.1	0.7	
Marshall Stability, lb	68	223	585	1490	709	834	1005	699	857	409	320	721	1079	1022	1430	1048	528	2480	2835	1411	2503
Flow, 0.01 in.	15	23	21	18	18	6	6	7	4	14	14	10	11	6	6	5	5	8	8	8	7
Immersion Stability, lb	0	0	0	0	0	446	437	216	432	60	0	31	80	343	390	239	120	436	499	340	711
Flow, 0.01 in.	--	--	--	--	--	5	5	7	5	10	--	7	10	5	4	5	7	7	9	9	8
Bulk Sp. Gr.	1.714	1.754	1.796	1.798	1.733	1.938	1.939	1.916	1.916	1.786	1.702	1.734	1.796	2.067	2.072	2.051	2.049	2.067	2.052	2.023	2.036
Unit Wt, pcf	106.9	109.5	112.0	112.2	108.2	121.0	121.0	119.6	119.6	111.4	106.2	108.2	112.1	128.9	129.3	128.0	127.9	128.9	128.0	126.4	127.0
Air Voids, %	32.3	29.6	26.4	26.1	26.0	23.1	21.9	21.9	21.2	28.5	30.6	28.5	25.1	16.4	14.7	14.6	13.9	17.0	16.7	16.5	15.1
VMA, %	39.5	38.7	37.9	38.2	41.8	28.2	28.8	30.3	30.7	33.8	37.7	37.3	35.0	22.3	23.1	24.5	25.0	25.1	26.1	28.0	28.1

Table 3 (Continued). Marshall Properties of Foamed Asphalt Mixtures - Series A (AC-10)

Aggregate	B-7				B-8				B-9	B-10	B-11	C-1				C-2			
Material	10% B1 90% B6				20% B1 80% B2				30% B1 70% B2	40% B1 60% B2	20% B1 80% B3	Story Co. Road Top Material (Crushed stone)				Shelby Co. Road Top Material (Crushed stone)			
Mix No.	FA3B7	FA4B7	FA5B7	FA6B7	FA4B8	FA5B8	FA6B8	FA7B8	FA4B9	FA4B10	FA4B11	FA3C1	FA4C1	FA5C1	FA6C1	FA3C2	FA4C2	FA5C2	FA6C2
Asphalt Content, %	3.0	4.4	5.2	6.6	4.0	4.8	5.7	6.4	4.4	4.3	4.1	2.9	4.2	5.0	6.2	3.2	4.0	5.3	6.0
Mixing m.c., %	6.5	6.6	6.7	6.9	6.8	6.6	7.8	6.2	7.7	7.7	7.9	7.5	8.9	8.7	6.2	5.6	5.9	6.5	5.8
Cured m.c., %	0.2	0.2	0.3	0.1	0.9	1.1	2.1	0.7	2.6	2.3	1.4	1.2	3.8	3.9	0.4	1.1	1.3	2.0	1.5
Marshall Stability, lb	77	580	1393	1420	4468	3173	3030	2329	3002	2540	204	0	252	467	445	1636	2891	2551	1558
Flow, 0.01 in.	13	8	5	5	7	7	7	8	8	8	8	-	32	21	20	10	9	11	12
Immersion Stability, lb	0	77	130	160	1383	1340	1134	861	-	-	-	0	0	0	0	83	494	655	278
Flow, 0.01 in.	-	7	8	8	8	9	8	10	-	-	-	-	-	-	-	11	20	15	25
Bulk Sp. Gr.	1.793	1.856	1.858	1.841	2.149	2.137	2.098	2.079	2.143	2.114	1.991	1.944	1.951	1.969	1.909	2.141	2.139	2.133	2.083
Unit Wt, pcf	111.9	115.8	115.9	114.8	134.1	133.3	130.9	129.7	133.7	131.9	124.2	121.3	121.7	122.9	119.1	133.3	133.4	133.1	129.9
Air Voids, %	28.5	24.6	23.6	22.9	13.6	13.1	13.7	13.6	13.6	7.5	11.4	21.2	19.4	17.8	19.1	12.4	11.5	10.3	11.5
VMA, %	33.8	32.3	32.8	34.3	21.9	22.9	24.9	26.1	22.6	16.1	19.2	26.7	27.4	27.3	30.2	19.1	19.8	20.9	23.4

Table 4. Results of Hveem, Hubbard-Field and K-tests--Series A (AC-10)*.

Aggregate	B-1	B-2	B-3	B-4	B-5	B-7	B-8	C-1	C-2
A. C. Content, %	4.1	4.3	2.8	4.1	4.4	5.4	3.9	4.1	3.8
Mixing m.c., %	11.4	7.0	8.1	5.6	7.7	7.3	6.2	7.9	6.6
Cured m.c., %	4.2	1.0	0.7	0.8	1.0	0	0.8	2.8	2.4
H-F Stability, lb									
140^{o}F, wet	0	1010	357	---	1307	520	1967	---	---
77^{o}F, dry	10,000+	3450	2903	---	9193	3333	9357	---	---
Absorption, %	Disint.	0.4	1.3	---	3.5	0.4	1.1	---	---
Bulk Sp. Gr.	1.93	2.02	1.81	---	2.12	1.89	2.16	---	---
Hveem Stability	80	22	27	39	62	26	31	47	59
Bulk Sp. Gr.	1.89	2.05	1.90	2.19	2.14	1.96	2.17	2.02	2.15
K-test - c, psi	---**	17.8	38.0	19.3	49.2	35.3	61.6	11.1	28.3
ϕ, degrees	---**	28.3	27.0	32.6	43.9	27.7	36.0	40.0	38.2
E, psi	---**	6100	12,000	7600	12,000	9000	15,800	4800	8100
Bearing Capacity, psi									
Based on Standard Marshall	5	191	31	272	347	320	721	7	357
Based on Immersion Marshall	0	100	7	113	70	18	194	0	25
Based on c and ϕ	---	341	674	482	2846	652	1931	467	1039

* AC-10

**Could not be determined due to large shrinkage of the specimens after cured.

- At optimum asphalt content, all aggregates except C-1 produced foamed mixes of excellent standard Marshall stability (140°F wet).
- Marshall flow values were not affected significantly or consistently by asphalt addition, in contrast with hot mixes.
- The bulk specific gravities of compacted foamed mixes were generally low.
- The air voids of compacted mixes determined on the basis of calculated maximum specific gravities of mixes (from percent and bulk specific gravity of aggregate, and percent and specific gravity of asphalt cement) and the measured bulk specific gravity of compacted mixes were higher than usually encountered in dense-graded hot mixes.
- Voids in the mineral aggregate (VMA) of compacted foamed mixes, computed from bulk volumes of aggregates in the mixes, were also high.
- Immersion Marshall stability values (after 24 hr in water at 140°F) for most of the foamed mixes were low. While this test may be unrealistically severe for evaluation of stabilized foam mixes, the results do suggest the need to evaluate water susceptibility of foamed mixes.

The following discussions deal individually with the characteristics of foamed asphalt mixes of the various marginal or ungraded soil-aggregates and their blends.

Loess (B-1): Fig. 6 shows the effect of adding 4.4 to 9.5% foamed

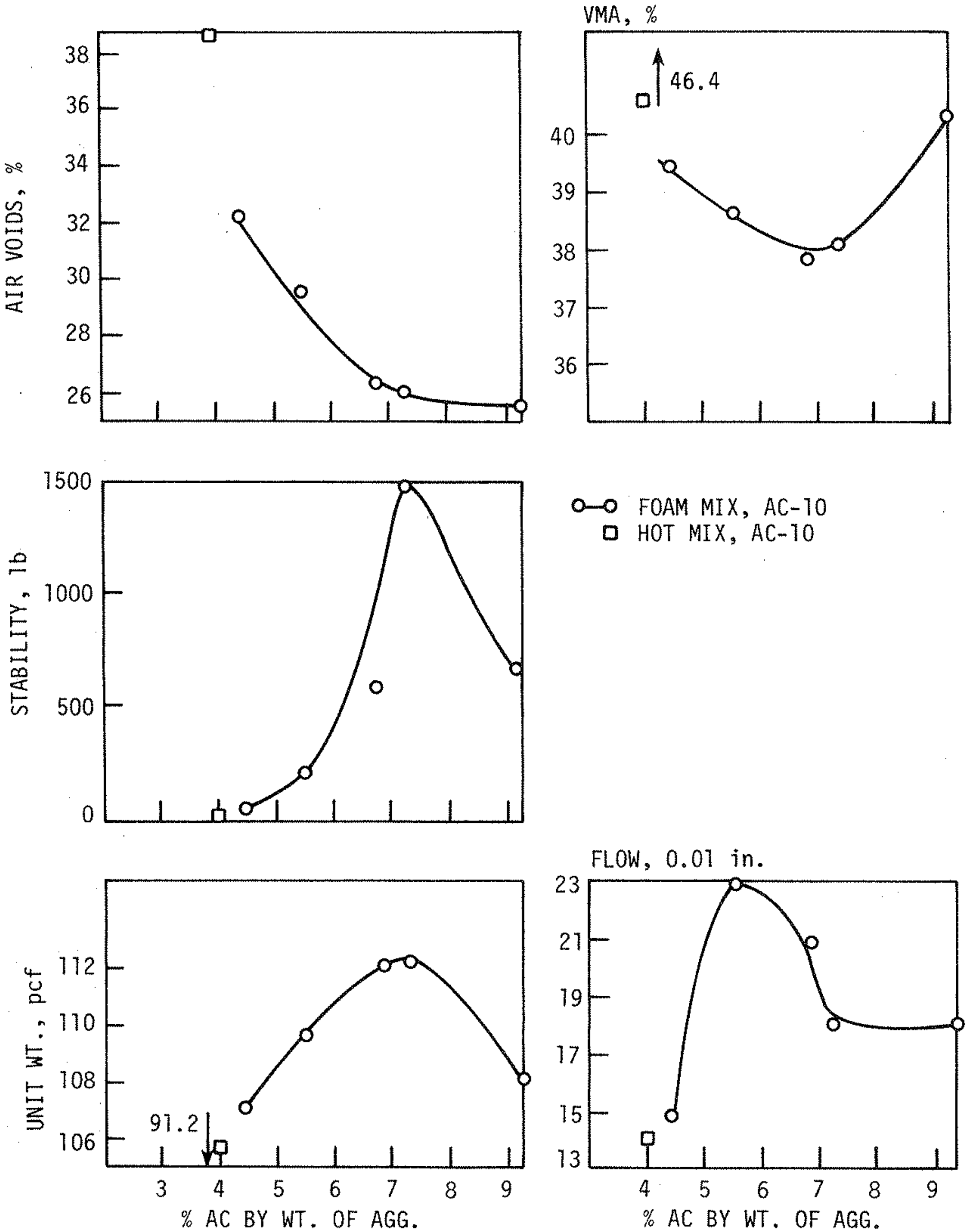

Figure 6. Marshall property curves of foamed asphalt mixes using B-1 with AC-10.

asphalt to this plastic loess on Marshall properties. Both standard stability and unit weight peaked at about 7.3% of asphalt. Although the foamed mix at this asphalt met stability and flow criteria for hot mix, the specimens collapsed upon immersion in water at 140°F for 1 hr. Because of high clay content of the soil, cured specimens showed hairline cracks. It is doubtful that this material can be effectively treated by foamed asphalt without blending with granular materials. Also due to the high clay content, the compacted foamed mix at 4% asphalt shrank to the extent that the K-test could not be performed.

Pit-run Sand (B-2): Fig. 7 shows the Marshall properties of this material stabilized with foamed asphalt between 3 and 5%. Maximum stability and unit weight occurred at 4% asphalt. However, flow values were low and erratic. Hubbard-Field stability (1 hr at 140°F) at 4.3% asphalt showed 1010 lb and an absorption value of 0.4% (Table 4). A similar material considered to be suitable for base construction or seal coated for lightly travelled roads was reported by Csanyi as a road sand from Maine. The corresponding Hubbard-Field stability from Csanyi's data was 420 lb (at 5% A.C.). The mixing moisture content of 7% was identical to the amount used for B-2. The freeze-thaw resistance of Csanyi's road sand mix was considered excellent. It is recommended that B-2 be considered as a candidate material for the Phase 2 field trial.

Blends of Loess (B-1) and Pit-run Sand (B-2): Csanyi's tests and experiences showed, and have been verified by new studies in Australia, that blending of fines (dirt or clay) with clean sands improved their stability. To test this, various percents of loess (from 20 to 40%) were

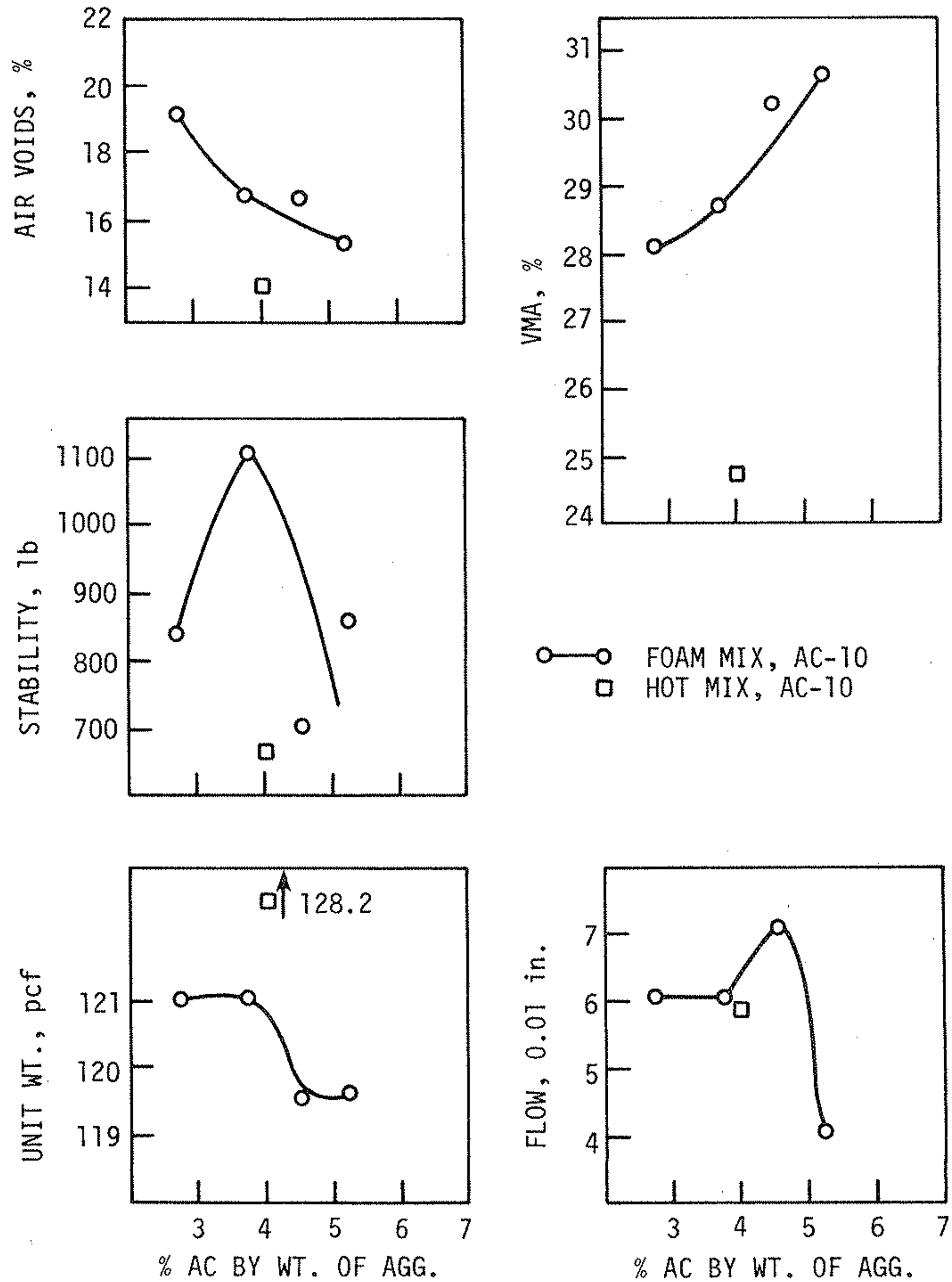

Figure 7. Marshall property curves of foamed asphalt mixes using B-2 with AC-10.

blended with pit-run sand and mixed with foamed asphalt. Figure 8 shows the Marshall properties of foamed mixes at 4 to 6% A.C. using 20% loess and 80% sand (B-8). The results were drastically increased unit weights (about 10 lb), reduced voids and improved flow values at all asphalt contents. The stabilities (both standard and immersion) were tripled at all asphalt contents (Table 3).

Marshall stabilities of foamed mixes at 4% asphalt were plotted against blending ratio in Fig. 9. Although as much as 40% loess could be blended with sand to produce acceptable mix (B-10), the optimum ratio for stability appears to be 20% loess and 80% sand (B-8). At 20% loess the percent passing No. 200 sieve was about 24%; at 40% loess the percent passing No. 200 sieve was 43%.

A foamed asphalt stabilized plant mix using materials similar to B-8 was tested by Csanyi in 1956 (10) on a pavement carrying 400 cars per day. The soil mixture was a blend of 75% fine sand and 25% loess. Six percent foamed asphalt (150/200 pen.) was added to the moist (8% water) soil. The material spread smoothly and compacted readily. A single seal coat was added to prevent surface scuffing. The test area received a second single seal a year later and performed excellently for more than three years.

It is interesting to note that Csanyi's loess/sand mix at 6% foamed asphalt had Marshall stability of 1100 lb compared to about 3000 lb for B-8; Csanyi's mix had a standard Hubbard-Field stability of 600-650 lb compared to B-8 at 4% A.C. of about 2000 lb. Also to be noted is that Csanyi had reported "good" freezing and thawing resistance based on laboratory study and field observation.

The Hubbard-Field and Hveem stabilities of loess-sand blend at 1:4

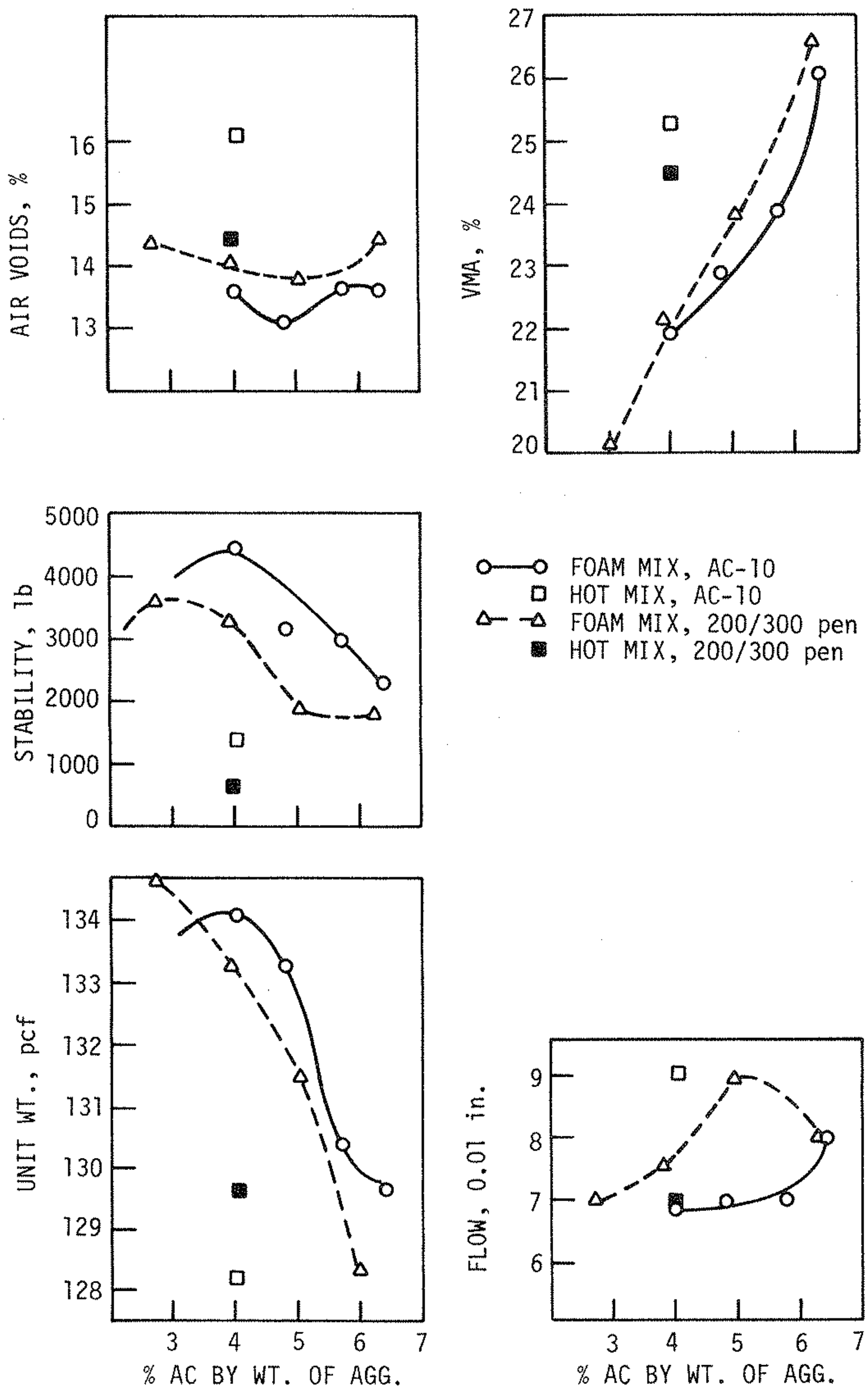

Figure 8. Marshall property curves of foamed asphalt mixes using B-8.

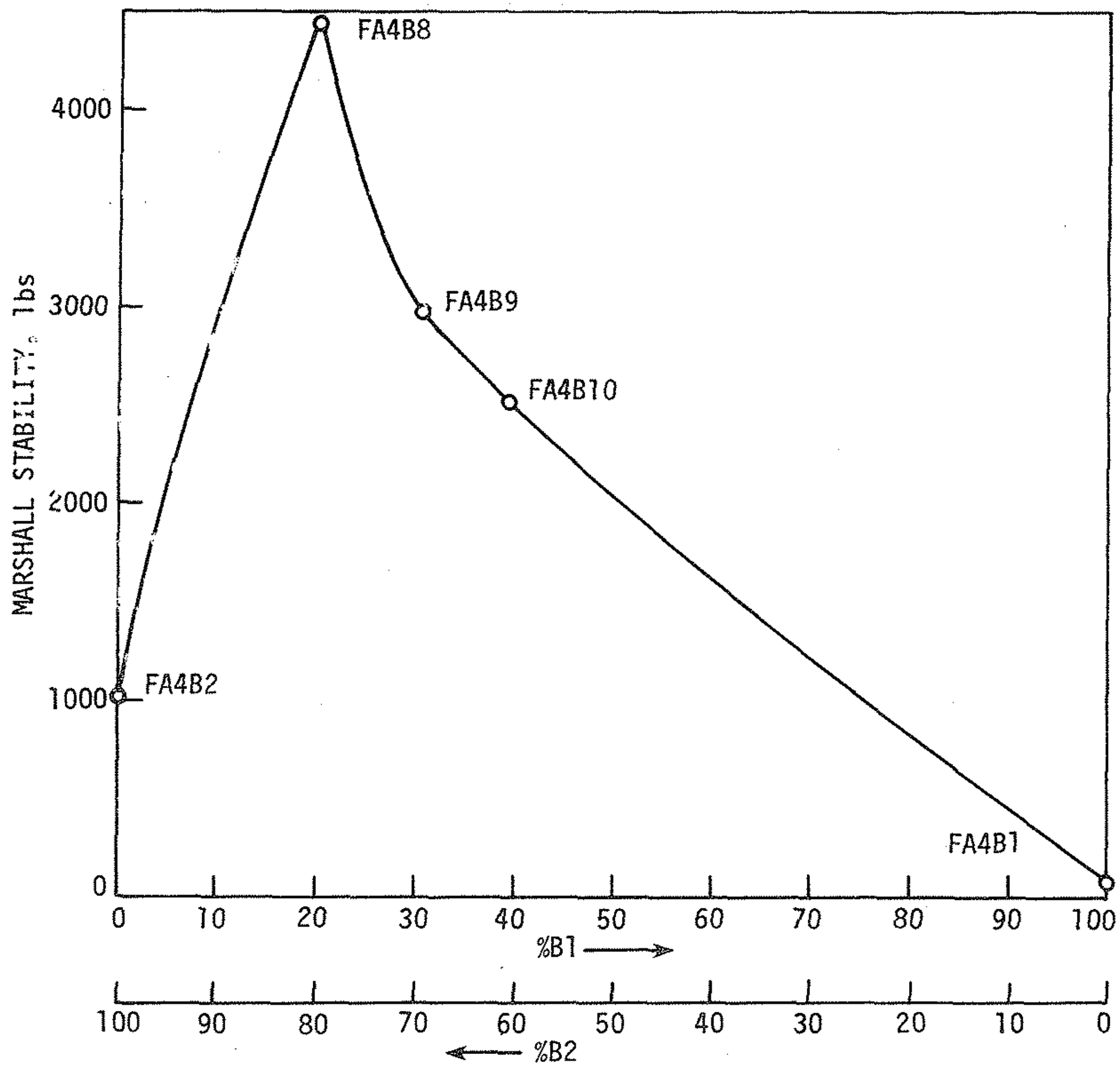

Figure 9. Marshall stability of pit-run sand (B-2) blended with varying percent of loess (B-1) - 4% foamed asphalt AC-10.

ratio (B-8) and at 4% foamed asphalt are given in Table 4. The Hubbard-Field stability of 1967 lb and Hveem stability of 31 met both design criteria for hot mix base and light traffic surface course.

Poweshiek Co. Blow Sand (B-3) and its Blend (B-11): Figure 10 shows Marshall properties of B-3 mixes at 3-6% foamed asphalt for both AC-10 and 200/300 pen. asphalt cements. The curves show trends quite different from what one would expect from hot mixes, especially the series with AC-10 asphalt. These unusual behaviors were reflected in the compacted densities. The Hubbard-Field and Hveem stabilities were also low. To meet Marshall design criteria with respect to stability and flow, 5.5% AC-10 is required. The addition of loess (B-11) further reduced the stability, as shown in Fig. 11. Several fine sands could be found in Csanyi's report that were similar to B-3 except that they contained 5-10% less passing No. 200 sieve. A Minnesota sand produced foamed mixes at 4-6% asphalt with Hubbard-Field stability in the range of 170-630 lb tested at 140°F wet, as compared to 360 lb obtained from B-3 (Table 4). However, the foamed asphalt mixes using Minnesota sand resisted 12 cycles of freezing and thawing, and were considered by Csanyi as suitable for base construction (10).

Pit-run Gravel (B-4): Figure 12 shows the Marshall properties of foamed mixes using the pit-run gravel with AC-10 at 3-6% range. Both stability and unit weight peaked at 4% asphalt. Flow values were low and not much influenced by asphalt content change. Marshall stability of 1400 lb and Hveem stability of 39 met stability requirements for hot mixes.

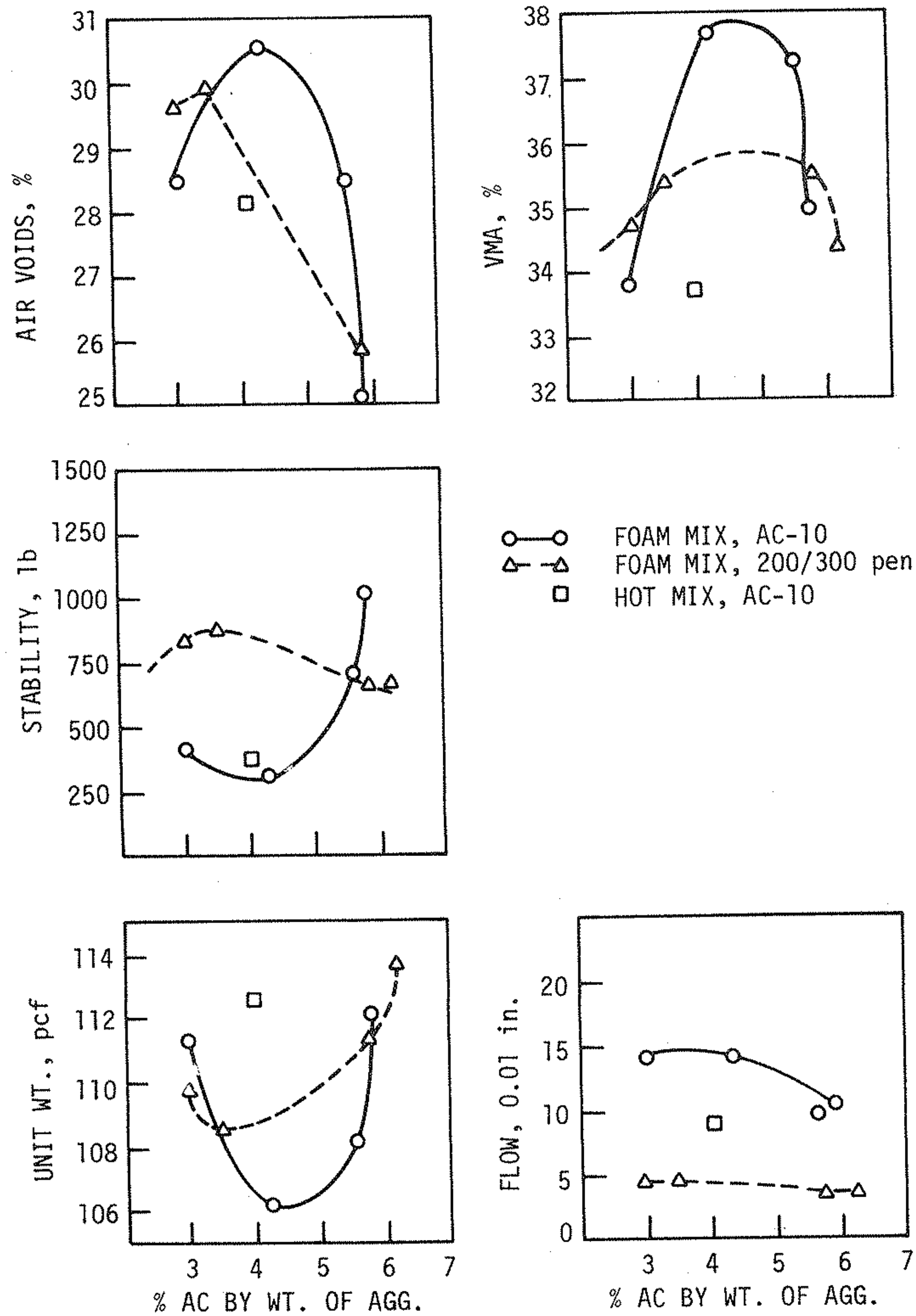

Figure 10. Marshall property curves of foamed asphalt mixes using B-3.

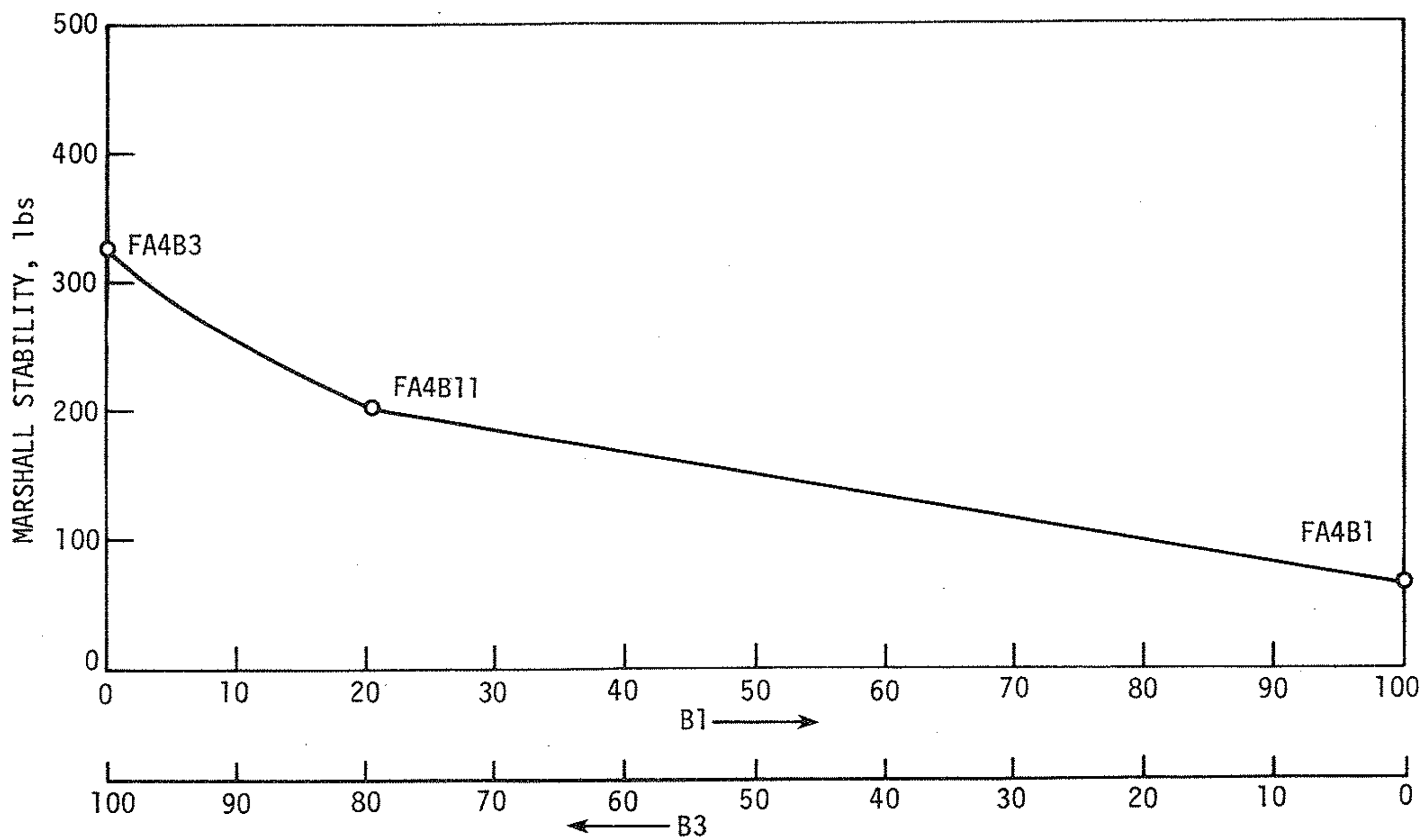

Figure 11. Marshall stability of foamed asphalt mixes at 4% AC-10 - aggregates B-1, B-3 and their blend (B-11).

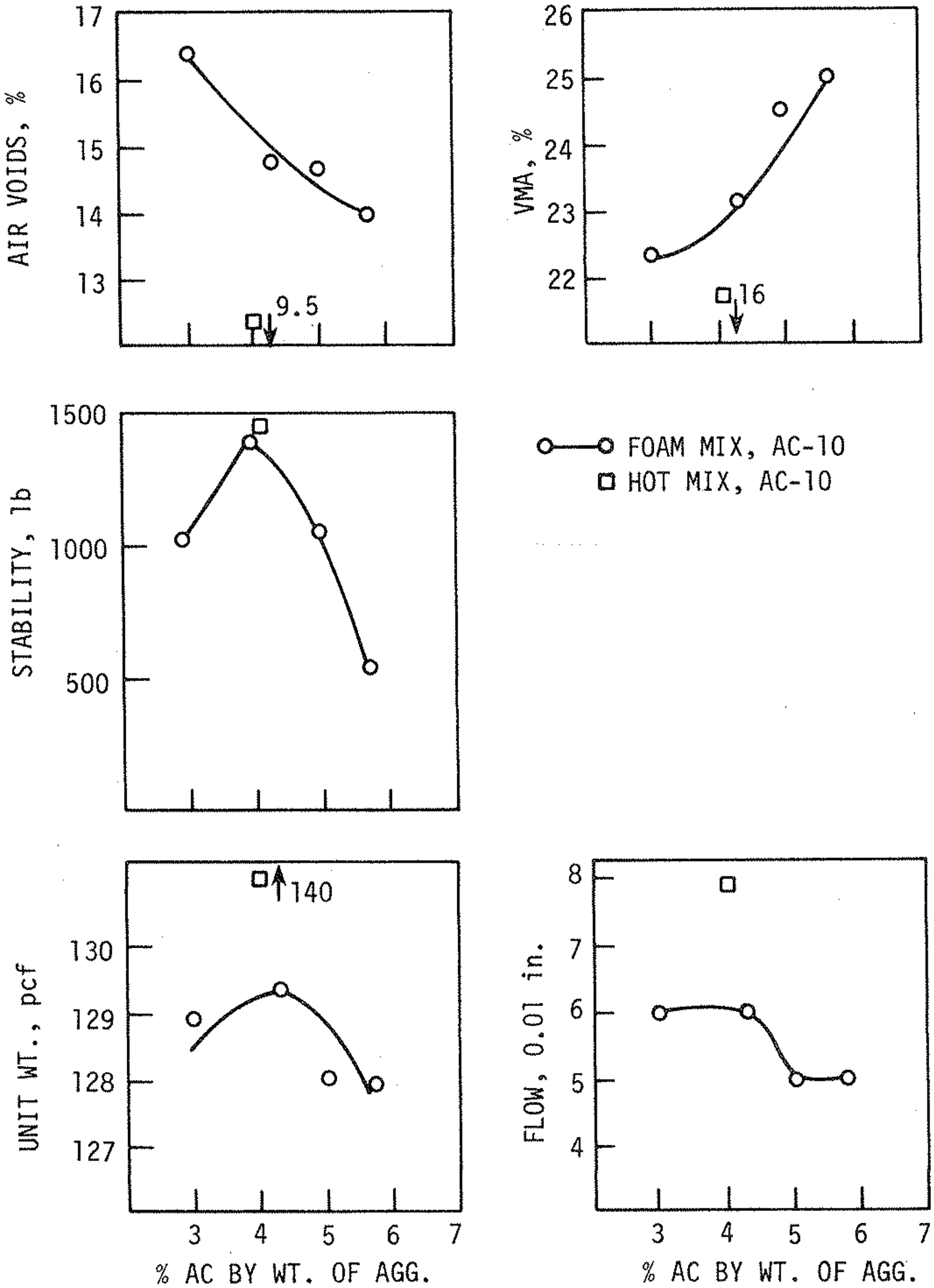

Figure 12. Marshall property curves of foamed asphalt mixes B-4 with AC-10.

Although a number of tests were conducted by Csanyi (10, 13) on using local ungraded aggregates in foamed asphalt cold mixes, only two aggregates were somewhat comparable to B-4. They were a Salt River gravel and a volcanic ash from Arizona. At 4-5% of 125 pen. foamed asphalt, these mixes had Hveem stability of 23-33. They were laid as surface course on a lightly travelled road in Maricopa County, Arizona, in 1960. Initial performance of the two-inch surfacing was "functioning satisfactorily under traffic." There is no record of long term performance.

Limestone Crusher Waste (B-5): Figure 13 shows Marshall properties of foamed mixes using a crusher waste material from Black Hawk Co. at 4-7% asphalt. This material produced foamed mixes of high stability (1400-2800 lb) and low but acceptable flow value of 8. At 4.4% asphalt the foamed mix had a Hubbard-Field stability of 1300 lb and Hveem stability of 62.

Csanyi reported test results of only two crusher waste materials for adaptability to stabilization by the foamed asphalt process (13). The two materials were identified as crusher waste and stone dust from Maine. The stone dust was somewhat like B-5 except for having 9% pass No. 200 sieve while 29% of B-5 passed through. The Maine crusher waste was a much coarser material than B-5. At 6% foamed asphalt the stone dust had a Hubbard-Field stability (140°F, wet) of 840 lb compared to 1300 lb for B-5. The Maine crusher waste had a Marshall stability at 140°F of 470 lb compared to 2500 lb for B-5 at 4% asphalt. Both of the Maine materials were considered suitable for base construction by the foamed asphalt process.

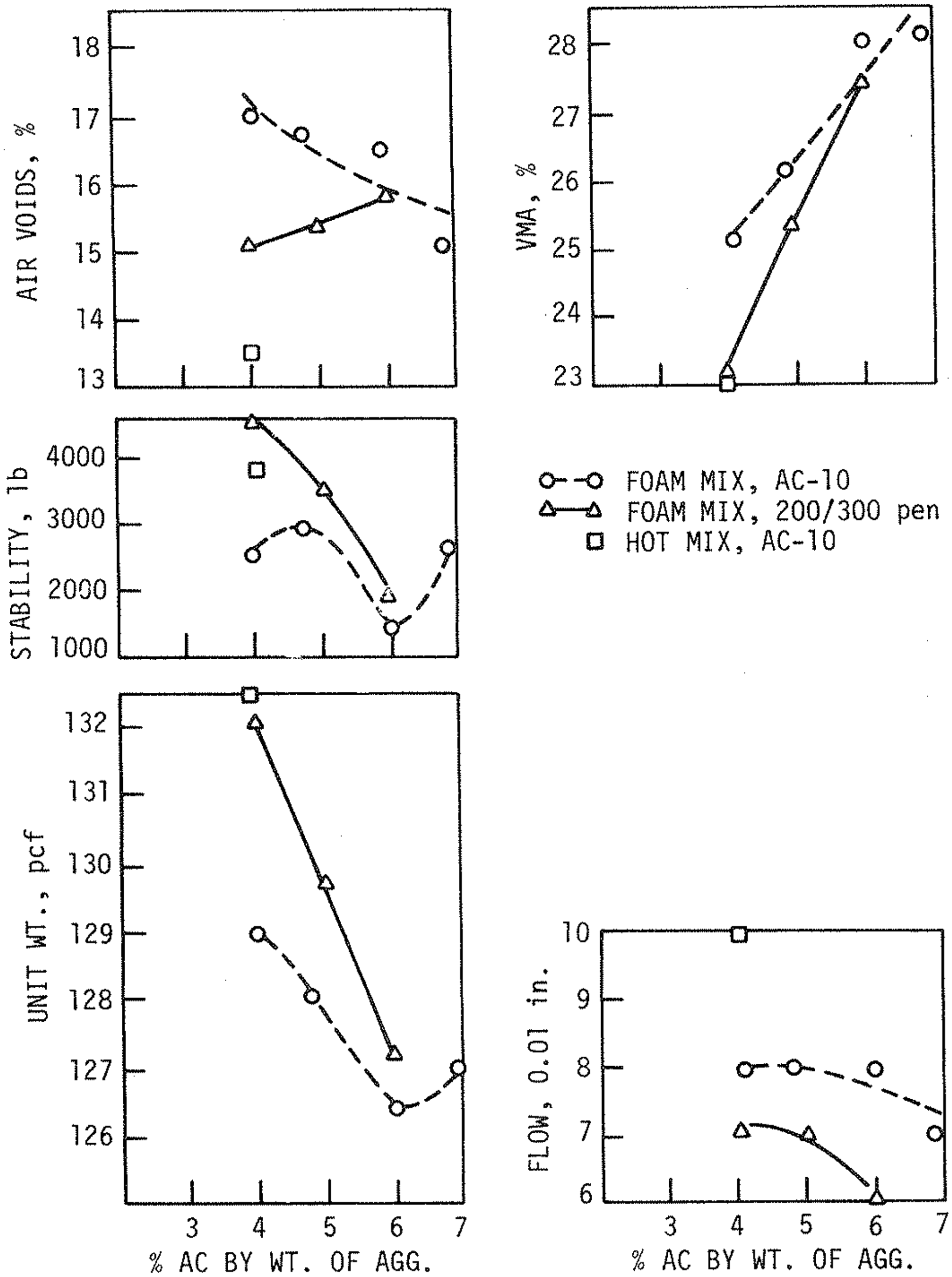

Figure 13. Marshall property curves of foamed asphalt mixes using crusher waste (B-5).

Blend of Shelby Co. Blow Sand (90%) and Loess (10%) - B-7: Figure 14 shows the Marshall properties of foamed mixes using soil mixture B-7 with asphalt content in the 3-7% range. The changes in physical properties due to increase in asphalt content were much like hot mixes except for flow value. At 4.5% asphalt this mix will meet both stability and flow criteria for hot mixes.

Among many sands tested by Csanyi perhaps a river sand from Minnesota and a beach sand from South Carolina were most similar to B-7 except for passing No. 200 sieve size. B-7 of this study contained 11% passing No. 200 sieve whereas the other two materials contained 4-7% passing No. 200 sieve. At 5% foamed asphalt the Minnesota sand and the South Carolina beach sand had standard Hubbard-Field stabilities of 440 lb and 600 lb respectively; at similar asphalt and mixing moisture content B-7 had a comparable stability of 520 lb.

One field project worth mentioning here when evaluating the blend of loess and blow sand for soil stabilization using foamed asphalt process was that of stabilization of six acres of six inches base for a parking lot in Sioux City, Iowa in 1959 (10). In this project in-place loess (almost identical to B-1) was blended with 33% locally available river sand (almost identical to B-6). The blend was stabilized with 6% foamed asphalt. The stabilized mix gave a standard Hubbard-Field stability of 400 lb and satisfactory resistance to freezing and thawing. Observations after one severe winter indicated that the parking area was in excellent condition. Of special interest is that the blended material in this project contained about 65% passing the No. 200 sieve.

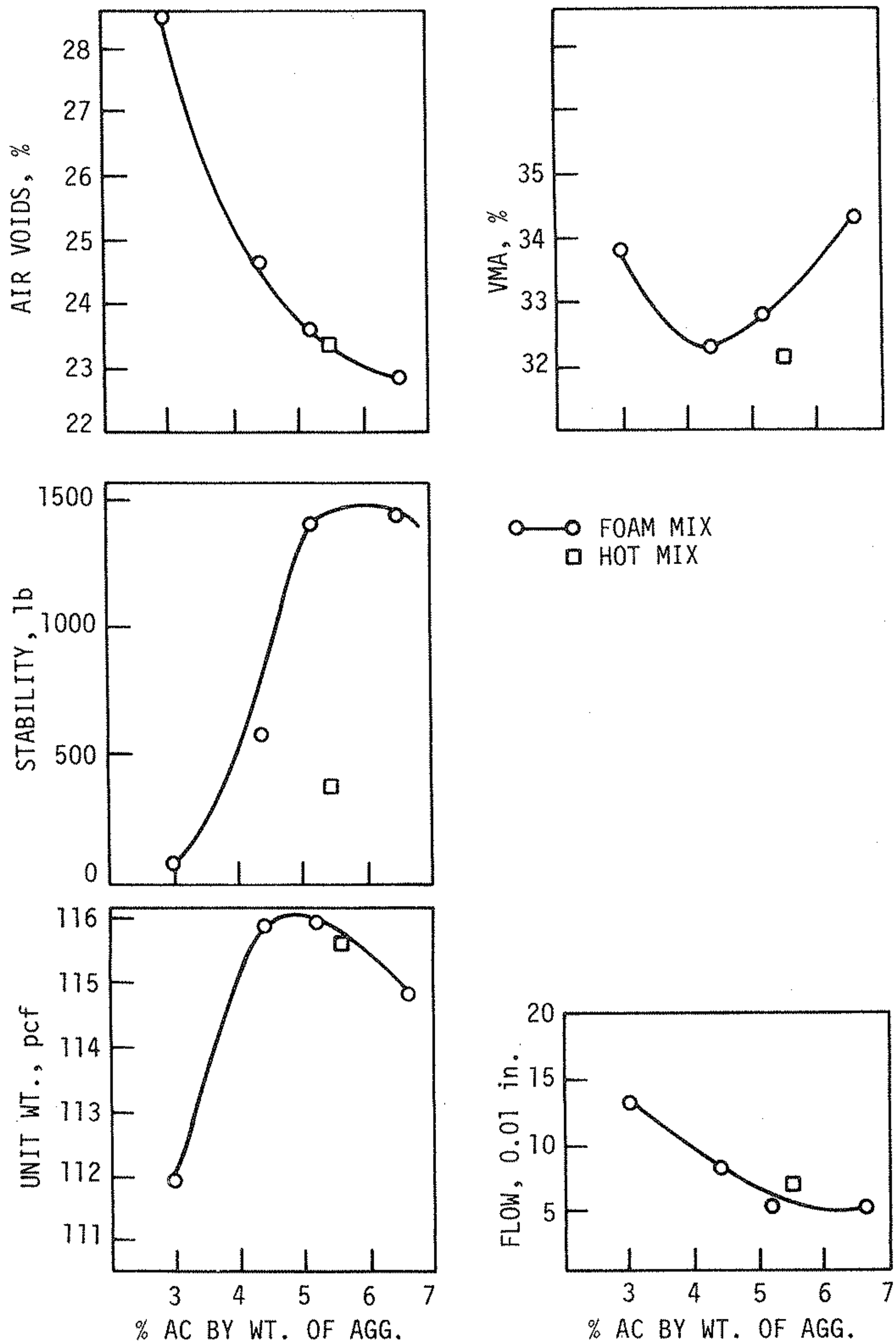

Figure 14. Marshall property curves of foamed asphalt mixes using 90% blow sand (B-6) blended with 10% loess (B-1) with AC-10.

Story Co. Road Surface Material (C-1): Figure 15 shows the Marshall properties of this material at 3-6% foamed asphalt. Both stability and unit weight peaked at 5% asphalt cement. At this asphalt content Marshall stability was 500 lb and flow was 21. Marshall specimens at all asphalt contents collapsed after immersion in water at 140°F for 24 hrs. Although the immersion condition used may be too severe for stabilized material, it does cause concern over the water susceptibility of foamed mixes using this material.

One job using material similar to C-1 involved the stabilization of an old county gravel road in Story Co., Iowa in 1957 (10). Soils in the top six inches of materials to be processed were predominantly A-6 (5) with plasticity index of about 14, much like C-1. Five percent of foamed asphalt was added to the material containing 9% moisture. Tests performed on the cores taken from the four inch compacted base showed Marshall stability of 420 lb, about what was obtained on the C-1 mix at the same asphalt content. The stabilized base was surfaced with a sand seal and gave excellent service for four years.

Shelby Co. Road Surface Material (C-2): Figure 16 shows the Marshall properties of foamed mixes using this material at asphalt contents in the 3-6% range. The curves show trends similar to hot mixes. At 4% foamed asphalt the mix yielded an excellent stability of 2900 lb and flow of 9, both meeting standard criteria for hot mix. The mix also showed excellent rsistance to water damage with an immersion stability of 490 lb.

Considering the excellent performance of a foamed mix of much lower stability similar to C-1 mixes, the test results on C-2 mixes suggest that this material, when stabilized with foamed asphalt, should perform well

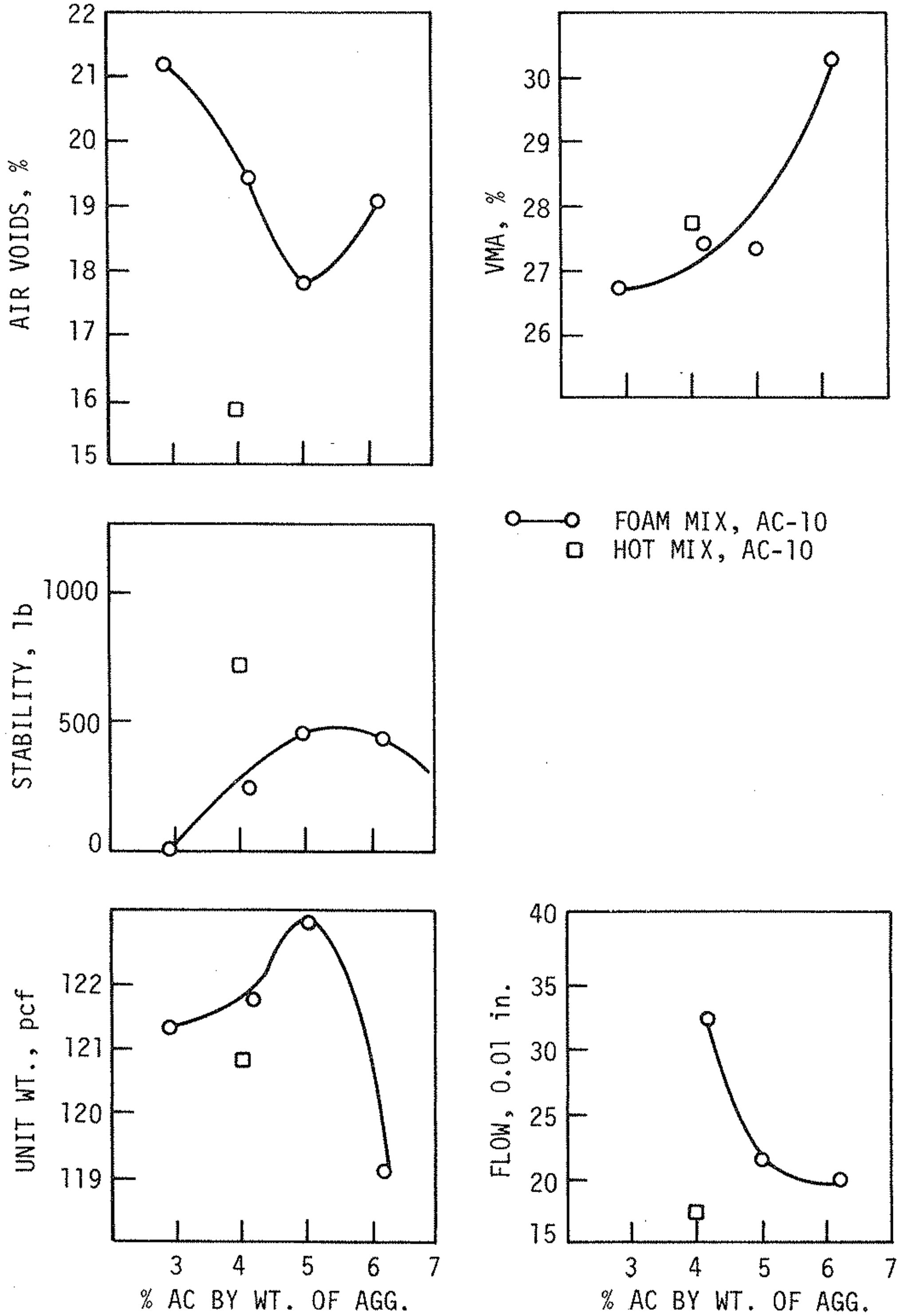

Figure 15. Marshall properties of foamed asphalt mixes using Story Co. road surface material (C-1) with AC-10.

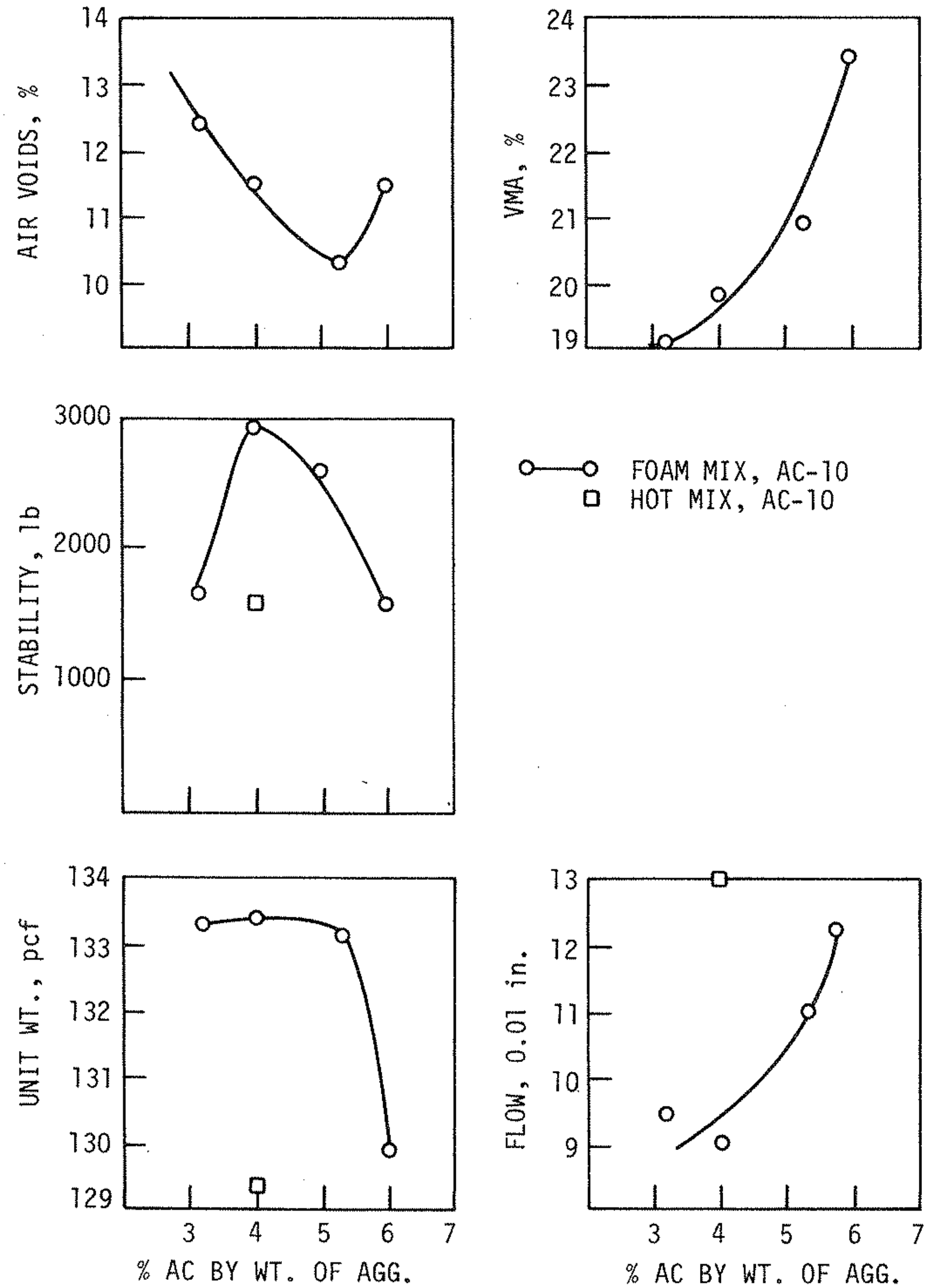

Figure 16. Marshall properties of foamed asphalt mixes using Shelby Co. road surface material (C-2) with AC-10.

as heavily travelled base, as county road surface with a light application of seal coat or, possibly as county road surface after the coarse particles over three-fourths inch in size were removed.

Based on Mohr theory of the strength of a confined specimen, both Metcalf (17) and McLeod (16) derived equations for calculation of bearing strength of paving mixtures using different approximations concerning the confining pressure in the pavement system. According to Metcalf, the bearing capacity of a paving mixture can be related to Marshall stability and flow by the following equation:

$$\text{Bearing capacity (psi)} = \frac{\text{stability}}{\text{flow}} \times \frac{120 - \text{flow}}{100}$$

Using this equation, bearing capacities of foamed mixes in Series A at approximately 4% AC-10 were calculated and are also given in Table 4. Bearing strengths of these mixes ranged from 0 for B-1 and C-1 after 24 hr immersion at 140^{o}F, to 720 psi for B-8 at standard Marshall condition.

To perform satisfactorily as surface without excessive plastic deformation, a pavement mxiture should have a minimum bearing capacity of 100 psi, the maximum loading imposed by truck tires.

Pavement performance data presented by Metcalf seemed to support this bearing capacity requirement as calculated from the Marshall test. According to this criterion, all foamed mixes in Table 4 except B-1, B-3 and C-1 would be satisfactory as surface mixes.

Using c and ϕ values, it is also possible to calculate bearing strength of paving mixture by the following equation, derived by McLeod (16):

$$\text{Bearing strength (psi)} = 2c \left(\frac{1 + \sin\phi}{1 - \sin\phi} \right)^{1/2} \left(\frac{2}{1 - \sin\phi - 0.2 \cos\phi} \right)$$

in which:

ϕ = angle of internal friction

c = cohesion, psi

Using this equation and values determined from Iowa K-tests, bearing strengths of foamed mixes using AC-10 were calculated and are given in Table 4. These values ranged from 341 psi for B-2 to 2846 psi for B-5 when tested at room temperature and dry. Since suggested design criteria based on bearing capacity are referring to tests performed either at 140°F or on saturated and soaked samples, it is difficult to evaluate these bearing strength values other than by showing their relative strength and the potential of Iowa K-test in evaluating stabilized materials.

However, the c and ϕ values derived from K-tests were plotted on the test evaluation chart provided by the Smith triaxial method (24). All eight mixes listed in Table 4 fell in the area considered to be satisfactory mixes. It is to be noted that, based on the Smith triaxial method of mix design, the specimens were tested at 75°F, approximately the temperature at which the Iowa K-tests were conducted.

4.3. Foamed Mixes - Series P (200/300 pen.)

The Marshall properties of foamed mixes using 200/300 pen. asphalt cement are given in Table 5. In general these properties are similar to those obtained from Series A (AC-10). The following discussions are concerned with cases where more interesting features are noted.

Poweshiek Co. Fine Sand (B-3): Marshall properties of this series of mixes are shown in Fig. 10. Although flow values were very low (lower

Table 5. Marshall Properties of Foamed Asphalt Mixes--Series P (200/300 pen.)

	B-3				B-4	B-5			B-6				B-7		B-8			
	FP3B3	FP4B3	FP5B3	FP6B3	FP4B4	FP4B5	FP5B5	FP6B5	FP3B6	FP4B6	FP5B6	FP6B6	FP4B7	FP5B7	FP3B8	FP4B8	FP5B8	FP6B8
Asphalt Content, %	3.0	3.5	5.8	6.2	4.2	4.0	5.0	6.0	2.8	4.1	5.2	6.0	3.8	5.5	2.7	3.9	5.0	6.3
Mix m.c., %	8.5	8.1	8.0	8.0	5.0	7.8	7.7	7.6	10.2	9.6	9.9	9.6	7.9	7.2	7.3	7.4	6.4	5.6
Cured m.c., %	0.3	0.2	0	0.1	0.2	0.4	0.4	0.5	0.8	0.4	1.0	0.6	0.4	0.3	0.9	1.0	0.2	0
Marshall Stability, lb	830	857	667	685	1006	4396	3280	1956	523	400	288	118	1783	1041	3607	3267	1978	1932
Flow, 0.01 in.	4	4	3	3	5	7	7	6	4	3	3	3	5	4	7	8	9	8
Bulk sp. gr.	1.76	1.74	1.78	1.82	2.15	2.11	2.08	2.04	1.67	1.73	1.75	1.77	1.90	1.90	2.16	2.14	2.11	2.06
Unit wt. pcf	109.8	108.6	111.4	113.7	134.0	132.0	129.7	127.2	103.6	108.1	109.3	110.0	118.4	118.4	134.6	133.1	131.5	128.3
Air voids, %	29.6	29.9	25.8	23.9	11.7	15.1	15.4	15.9	33.5	29.7	27.9	26.3	23.5	21.8	14.4	14.1	13.8	14.5
VMA, %	34.7	35.4	35.5	34.4	20.3	23.2	25.3	27.4	38.0	36.8	36.5	36.3	30.5	31.6	20.1	22.2	23.9	26.6

than corresponding mixes using AC-10), the Marshall stabilities between 3 to 6% asphalt ranged from 670 lb to 860 lb, and all met the minimum of 500 lb required for hot mix.

One foamed asphalt project using a fine sand almost identical to B-3 involved the base stabilization of 90 acres of parking lot of the baseball and football stadium in Minneapolis, Minnesota in the spring of 1961. In this project 4.5% of a 220 pen. foamed asphalt cement was added to the fine sand containing 8% moisture. This mix yielded a Hubbard-Field stability of about 3500 lb at 140°F dry and a moisture absorption of less than 1.5%. Comparable mix at 4.5% of 200/300 pen. foamed asphalt also at 8% mixing moisture (Fig. 10) for B-3 gave a Marshall stability of 750 lb. After three years, the parking lot required practically no maintenance and had served excellently (13). It was noted that during construction the temperature seldom exceeded 55°F, and work continued daily even when temperatures were as low as 39°F and during light showers.

Pit-run Gravel (B-4): The Marshall properties of B-4 at 4% 200/300 asphalt were comparable to the foamed mix at the same asphalt content using AC-10, except for lower stability.

Limestone Crusher Waste (B-5): The Marshall properties of foamed mixes using B-5 and 200/300 pen. asphalt cement are shown in Fig. 13. Both stability and unit weight were higher than corresponding mixes using AC-10 and peaked at about 4% asphalt. Flow values were lower than AC-10 mixes and again, not significantly affected by asphalt content.

Shelby Co. Blow Sand (B-6): The optimum asphalt content for B-6 using foamed 200/300 pen. asphalt cement appeared to be 3% asphalt. The Marshall stability at this asphalt content was 520 lb, lower than the optimum when blended with 10% loess (B-7) which yielded stability of 1800 lb for 200/300 pen. foamed mix (Table 4) and 1400 lb for AC-10 foamed mix (Table 3). All of the foamed mixes using B-6 had rather low flow values.

A number of foamed mixes using sands similar to B-6 (e.g., river sands from Sioux City, Iowa and Minnesota, beach sand from South Carolina, a sand from Alberta, Canada) were tested and judged by Csanyi (13) as suitable for base construction when used with 120-150 pen. foamed asphalt.

Blend of Pit-run Sand (80%) and Loess (20%) - B-8: Figure 8 shows the Marshall properties of foamed mixes using blended material B-8 and 200/300 pen. asphalt cement. Property curves of foamed mixes using 200/300 pen. were mostly parallel to those using AC-10, except stability and unit weight values were lower and flow values were higher. The foamed mix at 4% of 200/300 pen. asphalt would have met the Marshall stability and flow criteria for asphalt concrete.

4.4. Hot vs Foamed Mixes

Eleven hot mixes using both AC-10 and 200/300 pen. asphalt cements and two emulsion mixes using a CSS-1h were prepared at about 4% asphalt content and tested for Marshall properties. The results of these are given, together with corresponding foamed mixes, in Table 6. The following can be observed:

Table 6. Comparison Between Foamed Mixes, Hot Mixes and Emulsion Mixes

Aggregate	B-1		B-2		B-3				B-4			B-5		
Mix Type	Hot	Foam	Hot	Foam	Hot	Foam	Foam	Emul-sion	Hot	Foam	Foam	Hot	Foam	Foam
Mix No.	HA4B1	FA4B1	HA4B2	FA4B2	HA4B3	FA4B3	FP4B3	E683	HA4B4	FA4B4	FP4B4	HA4B5	FA4B5	FP4B5
Asphalt Type*	A	A	A	A	A	A	P	E	A	A	P	A	A	P
A.C. by wt of Aggregate, %	4.0	4.4	4.0	3.7	4.0	4.3	3.5	4.0	4.0	4.3	4.2	4.0	4.1	4.0
Mixing m.c., %	0	14.7	0	8.1	0	9.4	8.09	9.0	0	5.6	5.0	0	7.7	7.8
Cured m.c., %	0	-	0	-	0	-	0.2	0.4	0	0.4	0.2	0	1.0	0.4
Marshall Stability, lb	40	68	671	1005	371	320	857	886	1468	1430	1006	3730	2400	4396
Flow, 0.01 in.	14	15	6	6	8	14	4	4	8	6	5	10	8	7
Unit Weight, pcf	91.2	106.9	128.3	121.0	112.5	106.2	108.6	114.7	140.3	129.3	2.147	132.5	128.9	132.0
Bulk Sp. Gr.	1.462	1.714	2.055	1.939	1.803	1.702	1.740	1.838	2.248	2.072	134.0	2.124	2.067	2.116
Marshall Immersion Stability, lb	0	0	730	260	410	0	-	-	811	390	-	1238	397	-
Flow, 0.01 in.	-	-	8	6	18	-	-	-	9	4	-	18	7	-
Marshall Stability at 77°F, lb	-	-	-	2964	-	3106	-	-	-	-	-	-	8256	-
Flow @ 77°F	-	-	-	7	-	5	-	-	-	-	-	-	10	-

*A = AC-10, P = 200/300 pen., E = CSS-1h

Table 6 (Continued). Comparison Between Foamed Mixes, Hot Mixes and Emulsion Mixes

Aggregate	B-6		B-7			B-8				C-1			C-2		
Mix Type	Hot	Foam	Hot	Foam	Foam	Hot	Foam	Hot	Foam	Hot	Foam	Emulsion	Hot	Foam	Emulsion
Mix No. / Asphalt Type*	HP4B6 P	FP4B6 P	HA5B7 A	FA5B7 A	FP5B7 P	HA4B8 A	FA4B8 A	HP4B8 P	FP4B8 P	HA4C1 A	FA4C1 A	E6C1 E	HA4C2 A	FA4C2 A	E6C2 E
A.C. by wt of Aggregate, %	4.0	4.1	5.5	5.2	5.5	4.0	4.0	4.0	3.9	4.0	4.2	4.0	4.0	4.1	4.0
Mixing m.c., %	0	9.6	0	6.6	7.2	0	6.8	0	7.4	0	8.9	1115	0	5.9	6.6
Cured m.c., %	0	0.4	0	0.2	0.3	0	0.9	0	0.9	0	3.8	2.4	0	1.3	1.1
Marshall Stability, lb	0	400	397	1393	1041	1353	4468	670	3267	725	252	3882	1548	2891	3940
Flow, 0.01 in.	-	2.7	7	5	4	9	7	7	8	18	32	10	13	9	10
Unit Weight, pcf	110.3	107.5	115.6	115.9	118.3	128.2	134.1	129.7	133.1	120.8	121.7	125.8	127.6	133.4	134.8
Bulk Sp. Gr.	1.77	1.73	1.85	1.86	1.90	2.06	2.15	2.08	2.15	1.94	1.95	2.02	2.04	2.14	2.16
Marshall Immersion Stability, lb	-	-	-	164	-	-	1383	-	-	70	0	-	0	376	-
Flow, 0.01 in.	-	-	-	7	-	-	8	-	-	12	-	-	-	24	-
Marshall Stability at 77°F, lb	-	-	-	3275	-	-	-	-	-	-	-	-	-	8096	-
Flow @ 77°F, 0.01 in.	-	-	-	5	-	-	-	-	-	-	-	-	-	9	-

*A = AC-10, P = 200/300 pen., E = CSS-1h

- For standard Marshall stability, out of eleven comparable mixes, five foamed mixes (B-2, B-6, B-7, B-8, C-2) had higher stabilities than corresponding hot mixes; three foamed mixes (B-1, B-3, B-4) had about the same stability as corresponding hot mixes and only one hot mix (C-1) had higher stability value than the corresponding foamed mix. For the crusher waste (B-5), the hot mix had higher stability (3730 lb) than the foamed mix made with AC-10 (2400 lb) but lower than the foamed mix made with 200/300 pen. asphalt (4396 lb).
- Comparing the six sets of immersion stability data, all except one hot mix (C-2) had higher immersion stability values than corresponding foamed mixes.
- Perhaps due to the more intimate mixing, better coating and harder base asphalt used in the emulsion (CSS-1h), all three emulsion mixes produced Marshall specimens with much higher densities and stabilities than corresponding hot and foamed mixes.

4.5. Effect of Mixing Moisture Content

Both Professor Csanyi's original work on foamed asphalt soil stabilization (10, 20) and recent studies in Australia (5, 6, 18) showed the need for mixing water in the soil-aggregate before the addition of foamed asphalt. In Csanyi's experiments this ranged from about 6 to 10%. Concerning the required water in the soil aggregate, Csanyi wrote (10):

> "The water added to the aggregate during mixing softens the clayey materials or heavy soil fractions so that the agglomerations are broken up and uniformly distributed throughout the mix. The water also separates the fine particles and suspends them in a liquid medium, making channels of moisture through which the foamed asphalt may penetrate to coat all the mineral particles. The quantity of water is not critical, but sufficient water must be in the mix to make a satisfactory mixture. Excess moisture is undesirable because it makes the mix too soupy and may reduce coating of the aggregates. The proper quantity of water for any mix may be readily determined by a few trial batches."

Csanyi did not suggest methods that could be used to determine this "sufficient water" other than visual examination of the trial mixes ("insufficient moisture means a spotty mixture"), nor did he relate this moisture content to the optimum moisture content. From available data, it is estimated that the mixing moisture contents in his mixes would have been in the range of 60 to 80% of optimum.

Recent studies by Mobil Oil of Australia (18) suggest that the optimum mixing water content should be the "fluff point," a moisture content where the soil aggregate has its maximum bulk volume. This is approximately 70 to 80% of optimum moisture content as determined by AASHTO T99 (1, 22).

Because of the time limitation of the laboratory study, the foamed mixes in the two major series (Series A and P) where the major objective was to evaluate properties of the foamed mixes as affected by asphalt content, all mixes were prepared and compacted at about 70% of the optimum moisture content. In view of the importance of mixing moisture content on the properties of foamed mixes, a special series of mixes were prepared using soil-aggregates B-3, B-4, B-5 and B-7 in combination with approximately 4% 200/300 pen. asphalt cement.

In these mixes foamed asphalt was added to aggregates at ranges of moisture content from near zero to about 100% of optimum moisture content. Marshall specimens were molded, cured at 140°F for three days and tested. The results are given in Table 7. The Marshall stability versus mixing moisture content curves are shown in Fig. 17. All curves resemble the well-known Proctor moisture density curves. For each aggregate asphalt combination there existed an optimum mixing moisture content for maximum Marshall stability. The optimum mixing water content ranged from 6.5% for B-4 (pit-run gravel) to about 10.5% for B-3 (pit-run sand), corresponding to about 65 to 85% of optimum moisture content (AASHTO T99) for each aggregate.

Since the optimum mixing moisture content occurs at 65-85% of optimum compaction moisture content, a question arose as to the desirability of mixing at a moisture content 20-30% on the dry side of optimum and adding more moisture to bring the mix to its optimum for compaction. To investigate this question additional B-4 and B-7 foamed mixes were made at mixing moisture contents of about 70% of optimum. Water was then added to the mixes bringing the total moisture content to about optimum. Marshall specimens were compacted, cured and tested. The results showed that the additional moisture, though resulting in mixes at optimum compaction moisture content, lowered the stability values below those of the

Table 7. Effect of Mixing Moisture Content (200/300 pen.)

Aggregate	B-3				B-4						B-5			B-7				
Asphalt Content, %	4.1	3.5	4.0	3.9	4.0	3.9	4.2	4.1	3.9	4.1	3.7	4.0	4.1	3.5	3.8	4.1	3.8	4.7
Mixing m.c., %	5.4	8.1	9.9	12.1	0.3	2.7	5.0	6.5	8.4	5.7	5.8	7.8	10.1	5.5	7.9	9.5	11.0	7.7
% of OMC	43	65	80	97	4	33	61	80	102	70	48	65	84	50	70	86	100	70
Compaction m.c. (as % of OMC)	43	65	80	97	30	33	61	80	102	100	48	65	84	50	70	86	100	100
Cured m.c., %	0.1	0	0.3	0.4	1.4	0	0.2	0.5	2.0	2.7	0.2	0.4	0.2	0.7	0.4	0.4	0.5	0.4
Marshall Stability, lb	461	857	948	894	83	559	1006	1081	716	384	565	4396	2523	767	1783	1900	1539	1142
Flow, 0.01 in.	4	4	4	7	5	4	5	5	9	7	6	7	10	4	5	4	5	5
Bulk Sp. Gr.	1.78	1.74	1.78	1.83	1.77	2.11	2.15	2.18	2.15	2.12	2.05	2.12	2.07	1.86	1.89	1.91	1.87	1.87
Unit wt. pcf	111.1	108.6	110.5	113.9	110.3	131.3	134.0	135.7	134.0	132.4	127.6	132.0	129.1	115.8	118.4	119.0	116.9	116.9
Air Voids, %	27.5	29.9	27.9	25.9	28.3	13.7	11.7	10.7	11.9	12.9	17.9	15.1	16.8	27.1	23.3	22.8	24.5	23.5

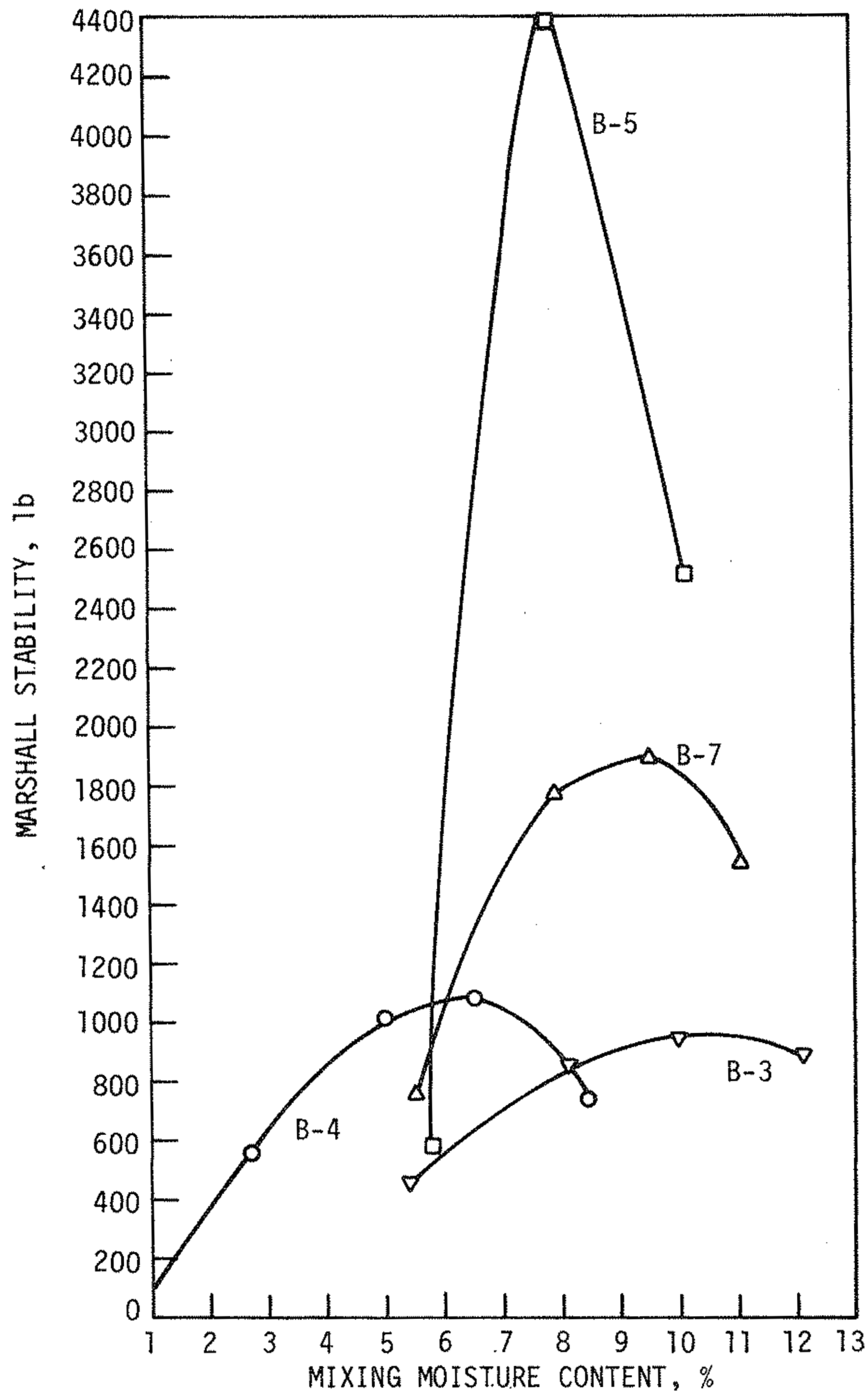

Figure 17. Effect of mixing moisture content on Marshall stability.

mixes mixed and compacted at 70-80% of optimum moisture content (from about 1000 lb to 380 lb for B-4; from 1900 lb to 1140 lb for B-7) and also below those of the equivalent mixes mixed and compacted at the same level of 100% optimum compaction moisture content (720 lb vs 380 lb for B-4 and 1540 lb vs 1140 lb for B-7).

To investigate the effect of additional moisture after foamed asphalt is made on the Marshall properties at extreme dry conditions, a foamed mix at 4% asphalt was prepared using B-4 at natural moisture content of about 0.3%. The foamed mix was spotty in appearance. Additional 2.1% moisture was added to the foamed mix (lowest moisture content that could be molded) making total moisture content of about 30% of optimum determined by AASHTO T99. The resulted Marshall stability was 80 lb, compared to 560 lb obtained from a similar foamed mix (B-4 at 3.9% asphalt) but mixed and compacted at about the same total moisture content of about 30% optimum.

To further analyze the relative effect of moisture content and asphalt content on Marshall stability of specimens molded and cured under identical conditions, a polynomial regression analysis was performed using all data obtained from B-4 and 200/300 pen. asphalt combinations. The equation of regression obtained was:

$$S = -4792 + 803M - 34M^2 + 1070A - 89A^2 - 42M \cdot A$$

where: S = Marshall stability, lb

M = mixing moisture content, % by wt of dry aggregate

A = foamed asphalt content, % by wt of dry aggregate.

While the multiple correlation coefficient ($R = 0.870$) indicates a less than best fit, the relative effect of moisture content versus asphalt content on Marshall stability can nevertheless be inferred. That is, the mixing moisture content is more important in a foamed mix than asphalt content as far as stability is concerned.

To summarize, data from the this series of tests appear to indicate:

- Mixing moisture content is extremely important in determining the physical properties of a foamed asphalt stabilized mix.
- The optimum mixing moisture content of a stabilized foamed asphalt mix is about 65 to 85% of the optimum content of the soil aggregate as determined by AASHTO T99.
- Additional moisture after foamed asphalt is incorporated in the mix has no beneficial effect.

4.6. Effect of Curing Conditions

Although foamed asphalt cold mix does not have the curing problems associated with cutback or asphalt emulsion, curing conditions must be considered in foamed asphalt cold mix design and evaluation. This is because (a) some premix moisture is always required for best mixing and coating of soil particles and (b) experience has indicated that cold wet foamed asphalt mixes tend to improve with age, traffic and temperature, all contributing to the removal of moisture in the mix.

In all of Professor Csanyi's published reports on his original work on foamed asphalt soil stabilization, he rarely referred to curing conditions when foamed asphalt properties were reported. However, a review of one of his unpublished notes (11) indicates that he did in fact consider curing conditions for his foamed mix designs. Two curing conditions were used: an air cure at room temperature for three days for mixes to be laid in cool weather and a warm cure at 120°F for three days for mixes to be laid in warm weather. Design criteria were given for both cases.

A laboratory testing procedure for the design of foamed asphalt soil mixtures proposed by Bowering (4) suggested that specimens be oven cured while in molds for three days at 140°F prior to testing. Laboratory studies performed in Colorado (1) used three types of curing conditions: three days at room temperature, one day at 140°F and three days at 140°F.

Because of the limited time and number of molds available, the standard curing condition during this project was three days at 140°F after specimens were extruded from the molds. However, in order to evaluate the effect of varying curing conditions on the Marshall properties and to make comparisons between results of this research with those of other studies easier, a special series of investigations on curing conditions was conducted using aggregate B-3 at approximately 4% asphalt (200/300 pen.). In this series, foamed mixes were mixed and compacted at about 8% moisture. Duplicate specimens were cured at room temperature (77°F) and 140°F, both in and out of molds, for various periods of time. Cured moisture contents, Standard Marshall stability and flow were determined. The results are given in Table 8 and plotted in Fig. 18. From these limited data the following can be observed:

- The gain in stability was accompanied by loss of moisture.
- As expected, stability gain and moisture loss occurred more rapidly when cured at higher temperature outside the mold than at low temperature while specimens were in the molds.
- When specimens were cured outside the molds, approximately the same stability resulted when cured to the same moisture content (e.g., seven days at 77°F and three days at 140°F; 21 days at 77°F and seven days at 140°F).
- At least for this particular aggregate, there appeared to be a critical moisture content above which no Marshall stability was developed.

One may question whether curing at 140°F (either in or outside the molds) really simulates or reproduces field curing conditions. It may be necessary to evaluate foamed mixtures both at early cured and ultimate cured conditions (e.g., three-days' cure at room temperature followed by vacuum desiccation for four days as recommended for emulsion mixes). One may also argue that, for mix design and evaluation purposes, laboratory

Table 8. Effect of Curing Conditions.

Aggregate					B-3				
Asphalt					200/300 pen.				
A.C. Content, %	3.9	4.0	4.0	4.0	3.9	3.9	4.0	3.9	4.0
Curing temp. °F	77	77	77	77	140	140	140	140	140
No. of days	3	7	7	21	1	3	3	7	7
In or outside of mold	out	out	in	out	out	out	in	out	in
Mixing m.c. %	8.0	7.6	7.6	7.6	8.0	8.0	7.6	8.0	7.6
Cured m.c. %	2.4	0.4	4.5	0.2	2.7	0.4	0.3	0.2	0.5
Marshall Stability, lb	0	840	0	1092	0	980	303	1125	270
Flow , 0.01 in.	-	4	-	3	-	4	6	4	5
Bulk Sp. Gr.	1.84	1.86	1.92	1.86	1.85	1.83	1.82	1.83	1.82

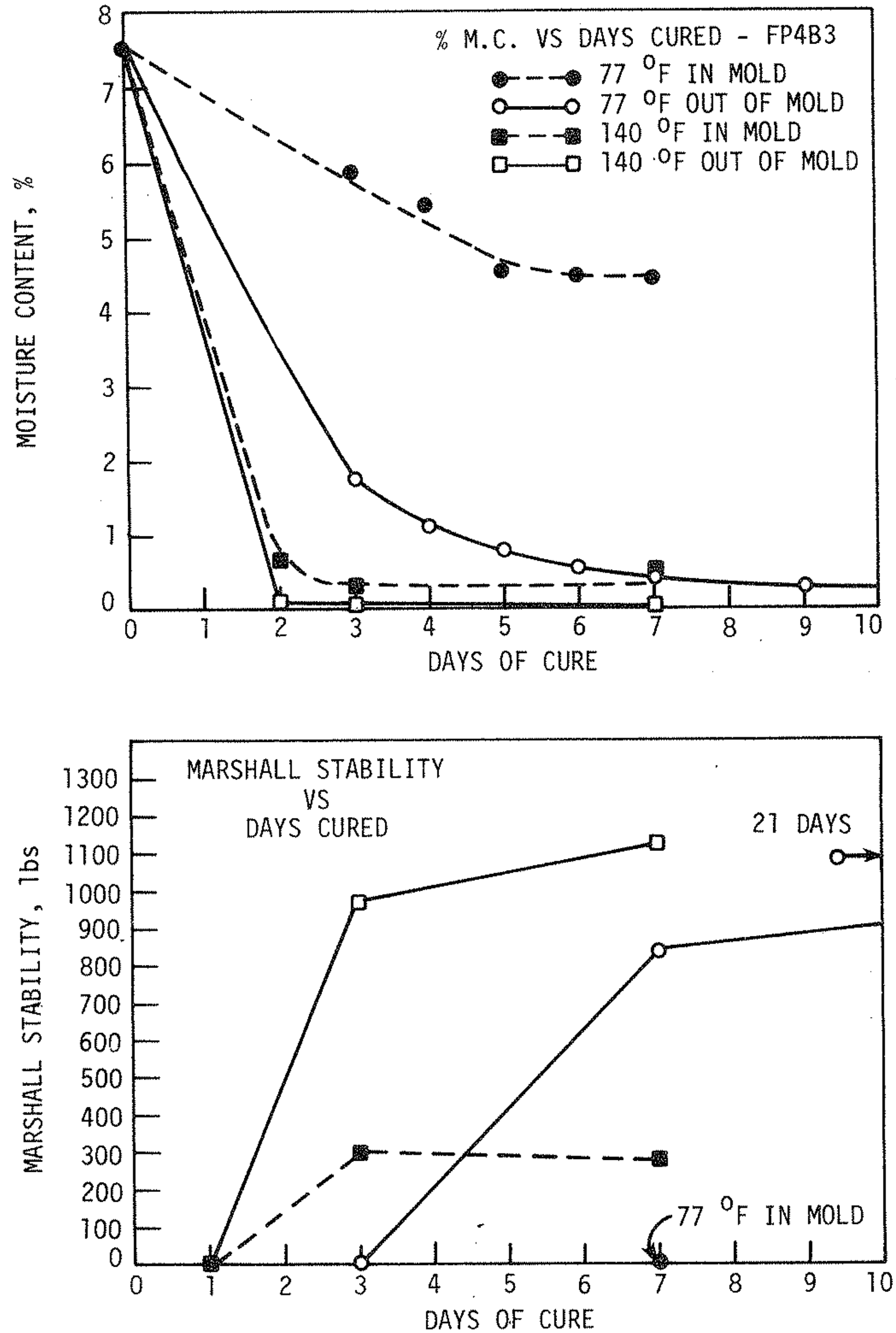

Figure 18. Effect of curing conditions on moisture content and stability.

curing conditions may not be important as long as results are correlated with field curing and strength gaining characteristics for a given climatic region. In any event, it is recommended that a detailed laboratory - field curing correlation be included in the next phase of study, the results of which will be useful in establishing criteria for foamed mixes.

4.7. Effects of Half-Life and Foam Ratio

Professor Csanyi (10) performed extensive study on the characteristics of foamed asphalt including types of foam (discrete vs concentrated), and factors affecting foam production such as nozzle tip dimension, nozzle adjustments, the asphalt temperature, the relative pressure of asphalt and steam. While there was no record indicating any asphalt that could not be foamed, there were no criteria as to what constituted a satisfactory foam, other than ~~by~~ visual examination of the foam and aggregate particle coating.

One of the improvements as a result of the Mobil Oil study in Australia was the quantitative characterization and development of criteria for the foam. The quality of foam is characterized by half-life and foam ratio. For soil stabilization the recommended foam ratio is 8-15 and half-life is a minimum of 25 sec (7, 14, 22). All foamed mixes made in this study were within these limits as determined by a one-gallon can.

Since there is little published data showing the effects of foam ratio (volume expansion) and half-life (foam stability) on the characteristics of foamed asphalt mixtures, a separate series of experiments was conducted using aggregate B-3 and 200/300 pen. asphalt cement. By varying the percent of anti-foam counter agent and cold water, seven batches of foamed mixes at about 4% asphalt were made at a half-life range of 11 to 136 sec and a foam ratio range of 5 to 20. Mixing moisture content was controlled at 70-80% of optimum for compaction of aggregate by AASHTO T99. Marshall specimens were molded, cured at 140°F for three days and tested for standard stability, immersion stability and one hour absorption. The results are given in Table 9.

Examination of the data revealed no significant trends. There were essentially no differences between mixes of high and low foam ratios (5 vs 20) and no differences between mixes of high and low half-lives (136 vs 11 sec.). The mix that had the highest stability values (standard and after 24 hour immersion at 140°F) was made with foam of 18 sec half-life and foam ratio of 15. These results are contrary to findings by Bowering and Martin (7) whose data showed significant improvement on a similar material (sandy loam) at 2.8% asphalt, when foam ratio was increased from 3 to 15. (The relative stability after a three-day exposure to moisture vapor was doubled; the unconfined compressive strength after a four-day soak was increased from 64 to 144 psi, and permeability was reduced by 50%.) It is possible that Marshall properties are not sensitive to the differences or that foamed mixes at higher asphalt content are less sensitive to foam quality changes.

Table 9. Effects of Half-Life and Foam Ratio on Marshall Properties (200/300 pen.)

Aggregate	B-3	B-3	B-3	B-3	B-3	B-3	B-3
A.C., %	3.5	3.5	3.5	3.3	3.5	3.9	3.9
Antifoam Counter Agent, %	0	0.1	0.3	0.7	1.0	1.0	1.0
Half-life, sec	18	11	16	39	40	136	86
Foam ratio	15	15	12	15	18	5	20
Mixing m.c., %	9.6	9.2	10.3	9.5	9.2	8.6	8.7
(% of OMC)	77	74	82	76	74	69	70
Cured m.c., %	0.3	0.3	0.5	0.3	0.2	0	0
Bulk Sp. Gr.	1.86	1.80	1.81	1.82	1.83	1.88	1.84
Marshall Stability, lb	1955	1250	1350	1078	1266	1202	1070
Flow, 0.01 in.	5	4	4	4	4	4	4
24 hr. Immersion Stability, lb	338	175	205	180	187	209	208
Flow, 0.01 in.	4	4	4	3	3	5	5
1 hr Absorption, %	0.13	0.17	0.29	0.14	0,20	0.26	0.27

4.8. CBR of Foamed Mixes

Since CBR is probably the most widely used index for soil stability as pavement material and in pavement design, this test was performed on three aggregates (B-1, B-4 and B-8) at about 4% foamed asphalt and ranges of mixing moisture content. The results are given in Table 10. For loess soil (B-1), there was little improvement at low mixing moisture content probably due to non-uniform distribution of asphalt and low compacted density thus high water absorption during the four-day soak period. When mixing moisture content was increased to 15.1% or 77% of optimum, the CBR value increased from 3 to 11, about the level of improvement reported by Nady and Csanyi (20). Similarly there was no improvement in CBR for the pit-run gravel (B-4) which had high CBR value without treatment. The low CBR of foamed mixes using B-4 was again due to the inadequate mixing moisture contents and the much lower resulted compacted density. Foamed asphalt mixes for B-8 (20% loess, 80% sand) showed the most significant improvement. When mixed and compacted at about 75% of optimum moisture content, the CBR of the foamed mixes increased by 20 fold after three days curing and increased from about 2 to 108 after seven days curing. Although the CBR data obtained in this study were limited, they did show the importance of controlling the mixture moisture content (and compacted density) and the large improvements for materials containing significant amounts of fines.

Table 10. CBR of Foamed Asphalt Mixes

Aggregate	B-1					B-4					B-8				
Series*	C	A	P		P	C	A	P		P	C	A	P		P
A.C. Content, %	0	3.9	4.2		4.2	0	4.1	4.0		4.0	0	3.9	4.0		3.9
Mixing m.c. %	19.6	10.7	11.8		15.1	8.2	5.3	4.8		5.8	10.1	6.6	7.4		7.6
(% of OMC)	100	55	60		77	100	65	59		71	100	65	73		75
As molded wet density, pcf	126.1	105.7	110.9		125.4	152.7	130.2	136.9		139.9	145.9	131.4	136.2		139.2
As molded dry density, pcf	105.4	95.5	99.2		108.9	141.1	123.6	130.6		132.3	132.5	123.3	128.0		129.4
Curing @ 140°F, days	0	3	3	7	3	0	3	3	7	3	0	3	3	7	3
Cured density, pcf	–	103.2	106.6	104.4	120.1	–	126.9	134.5	129.0	136.1	–	128.6	132.0	128.8	134.3
Cured m.c. %	–	8.1	6.7	3.0	10.2	–	2.6	1.3	0.4	2.9	–	4.3	2.9	0.9	3.8
CBR, %	3	2	4	4	11	46	4	21	45	20	2	11	31	108	20
Swell, %	2.5	2.8	3.0	5.5	1.8	0	0	0	0	0	0	0	0	0	0

*C = control; A = AC-10; P = 200/300 pen.

4.9. Freeze and Thaw Tests

One hot mix and one foamed mix, both at 4 percent asphalt of AC-10, were prepared for each of three aggregates: C-1 (Story Co. road material), B-6 (blow sand) and B-8 (20% loess blend with 80% sand). Three Marshall specimens were compacted from each batch. After three-days' curing at 140°F for foamed specimens, they were exposed to ASTM C666 Method B rapid freezing in air and thawing in water cycles. Eight 40 - 0 - 40°F cycles were run per day. C-1 specimens, both hot mix and foamed mix, stood 14 cycles in fair condition but disintegrated after a total of 52 cycles. All B-6 and B-8 samples underwent 70 cycles without disintegration. Marshall stability and flow were determined on these samples after 70 freezing and thawing cycles. The results are given in Table 11. Evidence from these limited results indicated that foamed mixtures were as resistant to freezing and thawing recycles as were hot mixes; at least one foamed mix, B-8, performed better than hot mix. It is also of interest to note that all foamed mixes met Csanyi's (10) 10 cycle freezing and thawing criteria for base material.

Table 11. Results of Freezing-Thawing Test

Aggregate	C-1		B-6		B-8	
A.C.	AC-10		200/300 pen.		200/300 pen.	
Mix Type	Hot	Foam	Hot	Foam	Hot	Foam
No. F-T Cycles	52	52	70	70	70	70
Resistance to F-T	D*	D	S*	S	S	S
Original Marshall Stability, lbs	725	250	0	400	670	3267
Retained Marshall Stability, lbs	0	0	0	221	375	2780
Percent Retained	0	0	-	55	56	85

*D = disintegrated; S = satisfactory

4.10. Effect of Lime and Portland Cement Treatments

In view of the relatively low Marshall immersion stability of most of the foamed mixes, it was decided to investigate whether the resistance of foamed mixes to water action could be improved by lime and portland cement treatment. Aggregate B-3 was selected for this study. Three batches of foamed mixes were prepared at about 70% of optimum moisture content and 4% asphalt cement. One batch contained no additive; one batch contained 2% hydrated lime; and one batch contained 2% portland cement. Three Marshall specimens were molded, cured and tested for stability after 24 hour immersion in water at 140°F. The results are given in Table 12. The foamed mix without additive had an immersion Marshall stability of 125 lb (standard Marshall stability was about 860 lb); the stability of the cement-treated foam mix was increased to 200 lb, whereas the lime-treated mix yielded an immersion stability of 560 lb, a fourfold increase.

While one may question the severity or the suitability of the test condition for evaluation of stabilized base material, the effectiveness of lime treatment in improving water susceptibility of stabilized foamed asphalt mix is apparent.

Table 12. Effect of Lime and Portland Cement Treatments

Aggregate	B-3		
A.C.	200/300 pen.		
A.C.%	4.2	4.1	4.4
Mixing m.c., %	8.0	8.1	7.9
Treatment	None	2% lime	2% p.c.
Cured m.s., %	0.3	0.6	0.7
Bulk Sp. Gr.	1.82	1.86	1.78
Marshall 24 hr immersion			
Stability, lb	125	559	223
Flow, 0.01 in.	4	5	5
Unit wt pcf	113.5	116.0	110.9

4.11. Foamed Asphalt Recycling

The feasibility of cold recycling by foamed asphalt process was explored using two salvaged asphalt pavement materials: a reclaimed asphalt treated base containing 2.0% asphalt from a 1979 Kossuth County, Iowa, recycling project and a salvaged asphalt concrete surface and binder course mixture from I-80 (Cass County) stockpiled in Stuart, Iowa, containing 5.2% asphalt. The type and amount of virgin aggregates and type and amount of new asphalt used in the foamed mixes were those designed for hot recycled mixes and used in the field. For the foamed mixes, the reclaimed materials were blended with the required amounts of virgin aggregates both cold to which various amounts of moisture were added; then the required percents of virgin asphalt were added as foam. For the Kossuth Co. material, reasonable mixing and coating was obtained when moisture content was increased to 5%. For the Stuart stockpile material, moisture content beyond 2% (up to 6%) did not improve the mixing and coating. Because the additional coarse crushed limestone particles called for were based on hot recycling mixture design and because of the selective coating of only the fine particles, characteristic of the foam process, distribution of additional foamed asphalt in the Stuart mixes was extremely poor. Marshall specimens were compacted at room temperature, cured and tested. Table 13 gives the results of foam recycled cold mixes as well as comparable hot recycled mixes. Although foam recycled Kossuth mix at 5% moisture met Marshall criteria for hot mixes, recycled cold mixes from both Kossuth and Stuart materials had stabilities and densities much lower than corresponding hot mixes. From the preliminary results, it appears that cold recycling using foamed asphalt has to be investigated on the basis of the cold recycling concept and compared with other cold recycling

Table 13. Foamed Asphalt Recycling

Code	D-1				D-2			
Material Source	Kossuth Co.				Stuart Stockpile			
% Salvaged Material	60%				65%			
% Virgin Aggregate	40% (Crushed gravel)				35% (Crushed limestone)			
A.C. Type	200/300 pen.				AC-10			
Mix Type	Foam			Hot	Foam			Hot*
Moisture Added, %	0	3	5	0	2	2	2	0
A.C. Content, %	4.0	4.1	4.1	4.0	1.4	2.2	4.3	1.5
Total Mix m.c., %	2.7	5.9	7.6	0	2	2	2	-
Cured m.c., %	0.5	1.1	1.4	0	0	0.1	0.1	-
Marshall Stability, lb	85	770	864	1394	173	94	175	2183
Flow, 0.01 in.	15	10	12	12	21	23	25	12
Bulk Sp. Gr.	1.93	2.02	2.06	2.27	2.07	2.07	2.02	2.42
Unit Wt, pcf	120.2	126.0	128.5	141.9	129.3	129.4	126.3	151

* From Ortgies and Shelquist (21)

alternatives (such as using cutbacks or asphalt emulsions) and that additional coarse virgin aggregates called for, based on hot mix recycling, may not be necessary or desirable. Additional research using either 100% reclaimed materials or additional fine virgin materials such as sands in conjunction with foamed asphalt should be undertaken and compared with cold recycling using cutbacks or emulsions.

4.12. Foamed Mix Design and Design Criteria

Although it has been 20 years since Professor Csanyi first developed the foamed asphalt process, to date only one set of laboratory evaluation procedures and criteria has been developed. This test procedure and associated design criteria were proposed by Bowering (4, 18, 19) based on studies by Mobil Oil in Australia. In this laborious procedure, foamed asphalt (1-4%) is added to the soil at the "fluff" point, the optimum mixing water content, and compacted cold by Hveem kneading compactor at an optimum compaction moisture content determined on the foamed asphalt mixture. The specimens are cured in molds at 140°F for three days. Six sets of tests are performed. The tests and suggested tentative limits for satisfactory foamed mixtures used immediately under thin seal coats are:

Test	Limit
1. Resistance R value at 77°F	
Cured	80 +
After 4-day soak at 77°F	80 +
2. Hveem Relative Stability at 140°F	
Cured	25 +
After exposure to moisture vapor at 140°F for 3 days	20 +

Test	Limit
3. Hveem cohesion at 140°F	
Cured	400 +
After exposure to moisture vapor	320 +
4. Unconfined compressive strength at 77°F	
Cured	150 psi +
After 4-day soak at 77°F	100 psi +
5. California permeability test at 77°F	
ml per 24 hours	50 -
6. California Swell test at 77°F	
free swell in 24 hours	0.030 in -

Due to the large number of specimens and molds required by the Mobil procedure and the very short time available in Phase I of this study, only Hveem stability was determined on selected materials at about 4% foamed asphalt. The results are given in Table 4. However, since curing conditions used in this study are different from those suggested by Mobil procedure (three days at 140°F extruded vs three days at 140°F in mold), these values must be viewed with caution.

Professor Csanyi used the Marshall method for design of graded and ungraded cold mixes using foamed asphalt. A series of trial mixes was prepared in which the moisture content in the aggregate and foamed asphalt content was varied. The mixes were tested for Marshall stability at 140°F and one-hour water absorption after three-days' curing at 120°F. The criteria for local light travelled road surfaces are: Marshall stability of at least 500 lb and a moisture absorption of less than 3% (11).

For foamed asphalt stabilized sands and soils for base construction Professor Csanyi relied on the Hubbard-Field method using 2-inch diameter specimens. The foamed mixes at different moisture and asphalt contents are tested for Hubbard-Field stability at 77°F, at 140°F after one hour in oven and after one hour in water at 140°F. The soil stabilized mixes are also tested for resistance to freezing and thawing. Specimens are cured for three days in air at room temperature if the mixes are to be laid in cool weather, and cured in an oven at 120°F for three days if the mixes are to be laid in warm weather. The design criteria, based on experience with mixes that gave satisfactory service under traffic for a year or more, were (11):

	Curing	
Test	3 Days at 120°F	3 Days at 77°F
Hubbard-Field Stability		
140°F wet, lb	500 +	300 +
Absorption, 1 hr	< 3%	< 5%
Freezing and thawing resistance after 10 cycles	Satisfactory	Satisfactory

Based on Professor Csanyi's design criteria, the following mixes can be tentatively considered acceptable and regarded as candidate materials for field trials in Phase II:

- pit-run sand (B-2) at 4% foamed asphalt cement.
- Poweshiek blow sand (B-3) at 4% foamed asphalt cement.
- Pit-run gravel (B-4) at 4% foamed asphalt cement.
- Crusher waste (B-5) at 5% foamed asphalt cement.
- Blend of 90% Shelby and 10% loess (B-7) at 5.5% foamed asphalt.
- Blend of 80% pit-run sand and 20% loess (B-8) at 4% foamed asphalt.
- Shelby County road surface material (C-2) at 4% foamed asphalt.

5. SUMMARY AND CONCLUSIONS

Thirteen aggregates and aggregate blands plus two recycled asphalt pavement materials were evaluated in conjunction with two asphalt cememts for foamed asphalt mixes. Foamed mixes were tested for Marshall, Hubbard-Field and Hveem properties and compared with equivalent hot mixes. Evaluations of the two main series of foamed asphalt mixes were supplemented by additional investigation on the effects of mixing moisture content, curing conditions, foam quality, lime treatment and freezing and thawing. Limited studies on CBR of foamed mixes and feasibility of foamed asphalt cold recycling were also performed. In all, more than 500 specimens were tested from 150 batches of foamed mixes.

Within the scope of this study and on the basis of materials evaluated, the following conclusions can be drawn:

1. Of eight materials tested, five can be designed by foamed asphalt process to meet either Hubbard-Field or Marshall criteria as suggested by Professor Csanyi. A sixth material (Shelby blow sand), because of lack of fines, can be successfully stabilized with foamed asphalt when blended with 10% loess.
2. As much as 40% loess can be utilized in conjunction with fine sand in foamed stabilized mixes.
3. No apparent differences could be detected between Csanyi's steam foamed asphalt and asphalt foamed by Mobil's cold water process.
4. Mixing moisture content in the soil aggregate is the single most important factor in foamed asphalt mix design. Proper

pre-mix moisture makes intimate mixing and better distribution of foamed asphalt possible and results in better compacted density and stability.

5. The optimum mixing moisture content varies with types of materials (percent passing No. 200 sieve), ranging from 65% to 85% of optimum moisture content determined by AASHTO T99.

6. In eight of 11 comparable mixes, foamed mixes had equal or higher Marshall stabilities than corresponding hot mixes of same aggregate, asphalt type and content. Only for aggregates B-3, B-5 and C-1 did hot mixes have higher stabilities than comparable foamed mixes.

7. No appreciable differences were found between foamed mixes made with AC-10 and 200/300 pen. asphalt cements.

8. Foamed asphalt cold mixes generally had low compacted densities, high voids and low resistance to water action as measured by Marshall stabilities after 24 hour immersion in water at 140°F.

9. Although gradation of sand is not critical to stabilization by foamed asphalt, addition of small amounts of fines (10 to 20%) to clean sand greatly improved the stability of the foamed mixes. This could be seen by comparison between B-3 and B-6, and between B-2 and B-8 at 4% foamed asphalt.

10. Although materials containing as much as 65% passing No. 200 sieve had been successfully stabilized by foamed asphalt, the realistic upper limit of percent passing No. 200 sieve is perhaps in the range of 35-40%. Limited data also showed that percent fines (passing No. 200 sieve) is more important in

judging the suitability of stabilization by foamed asphalt than plasticity index of the fines.

11. Marshall flow values of foamed asphalt cold mixes are not sensitive to asphalt content variations.
12. While no curing is required before compaction, foamed asphalt stabilized mixes do need curing to improve coating and to develop strength.
13. Within half-life of 10 to 140 sec and foam ratio of 5 to 20, no differences could be detected in the properties of resulting foam mixes.
14. Upgrading existing county road surface material by foamed asphalt is possible provided that the percent passing No. 200 sieve is not excessively high.
15. Cold mix recycling by foamed asphalt process is feasible provided that the mix design is based on cold mix recycling concept.
16. The addition of small amounts of either hydrated lime or portland cement improves the resistance to water action of a foamed mix.
17. Because of the effect of curing on the strength development of the foamed mixes, foamed mix design procedure and criteria should be locally based. These design criteria can be best established on the basis of laboratory-field correlations obtained from the field trials.

6. PROPOSED PHASE II WORK

In view of the energy, environmental and, above all, economic advantages of the foamed asphalt process, and the encouraging (although perhaps not surprising) results obtained in the laboratory phase of this study, field trials of promising foamed mixes with marginal local materials are recommended.

The objectives of the field trials will be:

- To evaluate the promising materials in foamed asphalt mixes as road surfaces and bases.
- To evaluate and/or generate construction and inspection tests and specifications.
- To correlate field strength characteristics and performances of foamed mixes with laboratory strength and other properties as functions of curing conditions, time and cured moisture content.
- To familiarize and document foamed asphalt construction techniques and problems.
- To establish locally based mix design criteria.

The laboratory aspect of field trials will consist of detailed design and evaluation of candidate materials, especially in terms of mixing and compaction moisture contents, strength properties at various stages of curing, testing of field-produced foamed mixes, and testing and analysis (including density, moisture content, strength, etc.) of field core samples at appropriate intervals. The field aspect of the field trial will include preconstruction site evaluation, construction procedure and

and documentation, post-construction evaluation such as deflection measurements, cracking surveys, rut depth measurements, etc. at appropriate intervals.

The detailed field test program (Phase II) will be formulated in consultation with Iowa DOT engineers and cooperating county engineers.

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I would like to dedicate this report to the late Professor Ladis H. Csanyi, who, as my major professor, first introduced me to the foamed asphalt and taught me much of what I know about asphalt.

8. REFERENCES

1. Abel, F. and Hines, C.R. (1979). Base Stabilization with Foamed Asphalt. Report No. CDOH-SMB-R-79 (FHWA-CO-RD-79-5), Colorado Division of Highways, Denver, Colorado.

2. The Asphalt Institute (1969). Mix Design Method for Asphalt Concrete and Other Hot-mix Types. MS-2, Asphalt Institute, College Park, MD.

3. Bowering, R. H. (1970). Upgrading Marginal Roadbuilding Materials With Foamed Bitumen. Highway Engineering in Australia. February 1970.

4. Bowering, R. H. (1970). Properties and Behavior of Foamed Bitumen Mixtures for Road-Building. Proceedings of the 5th ARRB Conference 5(6):38-57. Canberra.

5. Bowering, R. H. (1971). Soil Stabilization with Foamed Bitumen. Highway Engineering in Australia. October 1971.

6. Bowering, R. H. and Currie, D. T. (1973). Experience with Some Bitumen Treated Pavement Materials in Australia. 7th World Meeting, International Road Federation, Munich.

7. Bowering, R. H. and Martin, G. L. (1976). Applications of Foamed Bitumen. Proceedings of the Association of Asphalt Paving Technologists 45:453.

8. Csanyi, L. H. (1957). Foamed Asphalt in Bituminous Paving Mixtures. Highway Research Board Bulletin No. 160, p. 108.

9. Csanyi, L. H. (1959). Foamed Asphalt. Technical Bulletin No. 240. American Road Builders Association, Washington, D.C.

10. Csanyi, L. H. (1960). Bituminous Mixes Prepared with Foamed Asphalt. Iowa Engineering Experiment Station Bulletin No. 189. Iowa State University, Ames, Iowa.

11. Csanyi, L. H. (ca. 1960). Preparation, Test, Design Criteria of a Number of Foamed Asphalt Mixes. Unpublished Notes.

12. Csanyi, L. H. (1962). Foamed Asphalt for Economical Road Construction. Civil Engineering 32(6):62.

13. Csanyi, L. H. (1964). The Foamed Asphalt Process for Preparation of Bituminous Mixes. Unpublished Lecture Notes.

14. Geohring, B. H. (1980). Foamed Asphalt Construction in North Dakota. Paper Presented at the 15th Annual North Platte Asphalt Workshop. North Platte, Neb., March 20-21, 1980.

15. Handy, R. L. et al. (1978). The Iowa K-Test. Transportation Research Records 789:42.

16. McLeod, N. W. (1950). Application of Triaxial Testing to the Design of Bituminous Pavements. ASTM STP. 106.

17. Metcalf, C. T. (1959). Use of Marshall Stability Test in Asphalt Paving Mixture Design. Highway Research Board Bulletin 234:1.

18. Mobil Oil Australia Ltd. (1973). Foamed Bitumen - Cold Dustless Mixtures. Technical Bulletin Bitumen No. 5.

19. Mobil Oil Australia Ltd. (1975). Foamed Bitumen - Black Bases in Full Depth Asphalt Construction. Technical Bulletin Bitumen No. 7.

20. Nady, R. M. and Csanyi, L. H. (1958). Use of Foamed Asphalt in Soil Stabilization. Highway Research Board Proceedings 37:452.

21. Ortgies, B. H. and Shelquist, R. A. (1978). Recycling of Asphalt Concrete From I-80 in Cass County. Final Report HR-1011. Iowa Department of Transportation, Ames, Iowa.

22. Ruckel, P. J. (1978). Foamix Asphalt - An Alternative Mixing Method. Paper Presented at the 22nd Annual Kansas Asphalt Paving Conference. The University of Kansas, Lawrence, Kansas, November 1978.

23. Ruckel, P. J. et al. (1979). Foamix Asphalt Advances. Paper Presented at ASTM Committee D-4 Symposium on What's New in Asphalt Paving? San Diego, California, December 12, 1979.

24. Smith, V. R. (1949). Triaxial Stability Test for Flexible Pavement Design. Proceedings, Association of Asphalt Paving Technologists 18:63.