TREATING MARGINAL AGGREGATES AND SOILS WITH FOAMED ASPHALT

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INTRODUCTION

In the 1950s, Professor L. H. Csanyi (*1-6*) 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 277 kPa (40 psi) into heated asphalt cement at about 172 kPa (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.

Although Professor Csanyi had tried the use of water (as well as air, gases and foaming agents) in addition to steam to produce foamed asphalt, he opted to pursue the latter because ". . . the use of steam proved to be the simplest, most effective and efficient" (*2*). 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 one to two percent cold water and further allowing mixing of the foam through a suitable mixing chamber (*7, 8*). Mobil was granted a patent in Australia in 1971 and the patent has now been extended to at least 14 countries; some

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type of work related to foamed asphalt is being performed in at least 16 countries (*9*).

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.

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.

Based on experiments conducted in Australia (*10*), South Africa (*11*) and Colorado (*12*), 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), hot mix or stabilization using cutbacks.
- Significant cost savings can be realized if marginal aggregates are locally available or if binders have to be hauled from long distances.
- Minimum pollution problems 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.

The objectives of this 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.

METHODS OF INVESTIGATION

Materials

Soils and Aggregates

Six basic materials found in Iowa 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 100 to 150 mm) materials (crushed stone) were obtained. One was from Mortensen Road, south of Ames, Story Co. (C-1) and one was from the southeast corner of Shelby Co., designated as C-2.

To evaluate the feasibility of cold recycling using foamed asphalt, a reclaimed material from the Kossuth Co. 1979 recycling project and a salvaged crushed bituminous pavement from the I-80 Stuart stockpile were obtained together with virgin aggregates used in the respective projects.

Asphalt Cements

Two asphalt cements, an AC-10 and a 200/300 pen. grade were used in the study. The 200/300 pen. grade was included to compare with Professor Csanyi's results, most of which were from mixes using this grade asphalt cement.

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.

A Series (AC-10):

In this series 11 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 four percent foamed asphalt content. Hveem specimens for the nine major aggregates at about four percent 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 (*13*). To compare with hot mixes and emulsion mixes, Marshall specimens were prepared and tested at four percent asphalt content of hot mixes using AC-10 and at four percent residue content of emulsion mixes using CSS-1h.

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 four percent asphalt and tested for Marshall properties.

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 four percent were prepared at ranges of prewet mixing moisture content from near zero to 100 percent 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 four percent 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 property.
3. Effect of Foam Half-Life and Foam Ratio: Foamed mixes were prepared at about four percent asphalt cement 200/300 pen. using B-3 blow sand. Foam half-life (the time needed for the foam to collapse to half of its original volume) was varied from 11 to 136 sec and foam ratio (ratio of the volume of the foam to the volume of the unfoamed asphalt) was varied from 5 to 20. Standard Marshall specimens were molded, cured and tested for standard stability and voids, 24-hr immersion (at 60 C) stability and absorption.
4. CBR of Foamed Mixes: Foamed asphalt mixes at zero and four percent asphalt were prepared at several mixing moisture contents and compacted to standard Proctor density and cured at 60 C 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 four percent 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. 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.

Methods and Procedures

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.

Asphalt Cements

Asphalt cements were tested for penetration, specific gravity and viscosity at 60 C (140 F) and 135 C (275 F).

Foamed Asphalt Production

Foamed asphalt was produced by a foaming unit built by Conoco, Inc. and loaned to Iowa State University. 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: 157 to 163 C (315 to 325 F)
- water pressure: 310 kPa (45 psi)
- foaming water content: 1.5 to 2.0 percent by volume of asphalt
- air pressure: 179 kPa (26 psi)
- anti-foam counter agent AN480: 0.4 to 0.7 percent by wt. of asphalt (to counteract anti-foaming agent that might have been added to the asphalts during refining processes)

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 (three to six percent) after the moisture content of aggregate was adjusted to about 70 percent of optimum moisture content as determined by AASHTO T99. The mixes, 3.5-5.0 kg per batch, were prepared in a 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 samples 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 the series cured under special conditions, all specimens were compacted at room temperature, extruded from the molds and cured at 60 C (140 F) for three days before tests were performed.

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 60 C using an automatic recording Marshall tester. Marshall immersion tests were performed on some series after the cured specimens were immersed in water at 60 C for 24 hrs.

Hubbard-Field foam mix specimens of 50.8 mm (2 in.) in diameter by 25.4 mm (1 in.) high were compacted at room temperature and cured, then tested at 25 C dry, after one hour in an oven at 60 C and after one hour in water at 60 C following The Asphalt Institute procedure (*14*).

Hveem specimens in all foamed mixes were compacted at room temperature using a kneading compactor, cured and tested at 60 C 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 and after specimens were cured at 60 C while in the mold.

The Iowa K-test was performed on foamed mixes compacted at room temperature to standard Proctor sample size following AASHTO T99 compaction, cured at 60 C for three days, and tested at room temperature according to the procedure described by Handy et al. (*13*). In this test the specimens were subjected to vertical compression at a rate of 1.27 mm (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.

RESULTS AND DISCUSSION

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 nonplastic A-1-b (B-2) to plastic loess A-7-6 (B-1). The gradation curves of these aggregates are shown in Figures 1-5. The physical properties of the two asphalt cements are given in Table 2.

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 Sieve Size	% Passing							
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, kg/m^3	1647	1903	1831	2196	2031	1703	1818	2063
pcf	102.8	118.8	114.3	137.1	126.8	106.3	113.5	128.8
Optimum Moisture Content, %	19.6	10.3	12.5	8.2	12.1	15.7	15.1	8.8

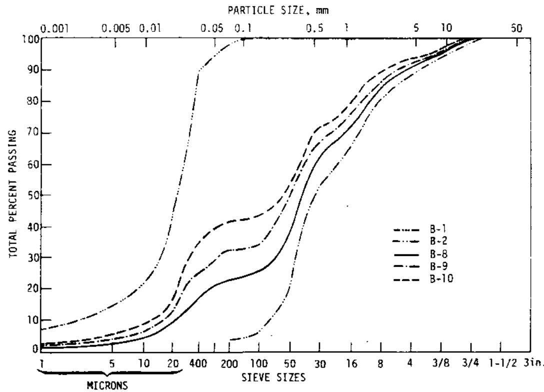

Fig. 1. Gradation of Aggregates B-1, B-2 and Their Blends (B-8, B-9, B-10).

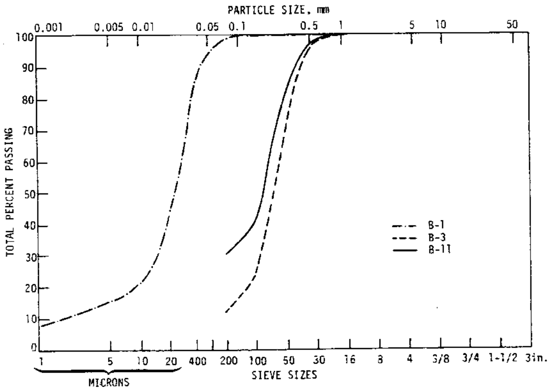

Fig. 2. Gradation of Aggregates B-1, B-3 and Their Blend B-11.

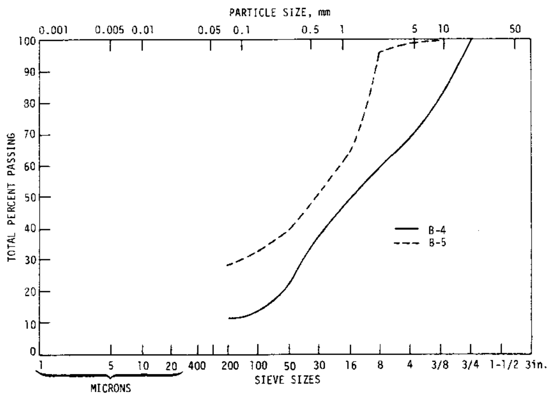

Fig. 3. Gradation of Aggregates B-4 and B-5.

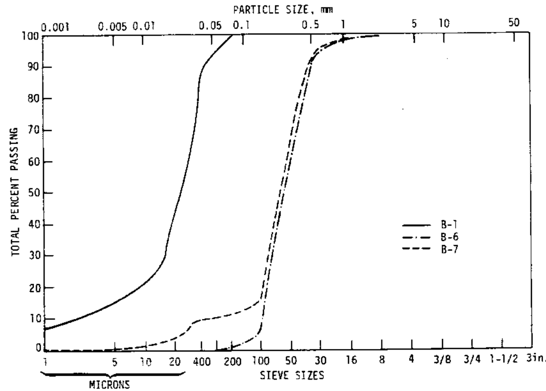

Fig. 4. Gradation of Aggregates B-1, B-6 and Their Blend B-7.

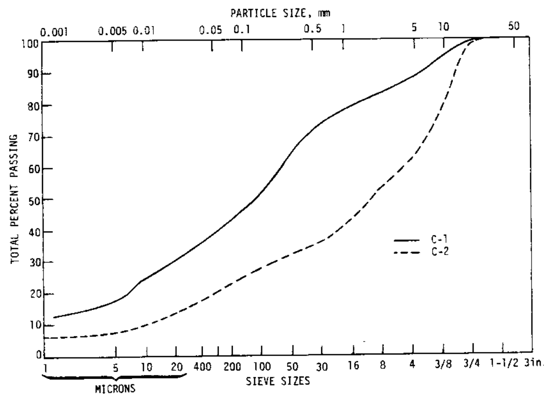

Fig. 5. Gradation of Road Surface Materials C-1 and C-2.

Table 2. Properties of Asphalt Cements

A.C. Grade	200-300 pen. (P)	A.C. 10 (A)
Penetration @ 25 C (77 F)	217	84
Viscosity @		
60 C (140 F), P.	413	1556
135 C (275 F), cS+	173	320
Sp. Gr. 25/25 C	1.001	1.026

Foamed Mixes–Series A (AC-10)

The general appearance and characteristics of foam and foamed asphalt stabilized cold mixes using the water/air foaming unit were not 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 percent 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 6.4 mm (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.

Since no appreciable differences were found between foamed mixes made with AC-10 and 200/300 pen. asphalt cements, unless otherwise noted only results from Series A (AC-10) mixes are presented. 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 four percent AC-10 are given in Table 4. The mixes were all prepared at ambient temperatures. The mixing and compaction moisture contents were approximately 70 percent of optimum moisture content determined by AASHTO T99. Several features are common to all foamed mixes of a given soil aggregate:

- At optimum asphalt content, all aggregates except C-1 produced foamed mixes of excellent standard Marshall stability (60 C 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 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 60 C) 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.

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

Aggregate	B-1					B-2			
Material	Loess					Pit-run sand			
Mix No.	FA4B1	FA5B1	FA6B1	FA7B1	FA9B1	FA3B2	FA4B2	FA5B2	FA6B2
Asphalt Content, %	4.4	5.5	6.8	7.3	9.5	2.7	3.7	4.5	5.2
Mixing m.c., %	14.7	14.7	14.7	14.7	9.8	7.1	7.1	7.1	7.1
Cured m.c., %	4.2	--	1.8	—	2.4	—	1.0	—	0.1
Marshall Stability, lb	68	223	565	1490	709	834	1005	699	857
Flow, 0.01 in.	15	23	21	18	18	6	6	7	4
Immersion Stability, lb	0	0	0	0	0	446	437	216	432
Flow, 0.01 in.	—	—	—	—	—	5	5	7	5
Bulk Sp. Gr.	1.716	1.754	1.796	1.798	1.733	1.938	1.939	1.916	1.916
Unit Wt. pcf	106.9	109.5	112.3	112.2	108.2	121.0	121.0	119.6	119.6
Air Voids, %	32.3	29.6	26.4	26.1	26.0	23.1	21.9	21.9	21.2
VMA, %	39.5	38.7	37.9	38.2	41.8	28.2	28.8	30.3	30.7

Aggregate	B-3				B-4				B-5			
Material	Fine sand				Pit-run gravel				Crusher waste			
Mix No.	FA3B3	FA4B3	FA5B3	FA6B3	FA3B4	FA4B4	FA5B4	FA6B4	FA4B5	FA5B5	FA6B5	FA7B5
Asphalt Content, %	3.0	4.3	5.6	5.8	3.0	4.3	5.0	5.7	4.1	4.8	5.9	6.9
Mixing m.c., %	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., %	1.0	0.8	1.1	0.7	—	0.8	--	--	1.0	0.1	0.7	
Marshall Stability, lb	409	320	721	1079	1022	1430	1048	528	2480	2835	1411	2503
Flow, 0.01 in.	14	14	10	11	6	6	5	5	8	8	8	7
Immersion Stability, lb	60	0	31	80	343	390	239	120	436	499	340	711
Flow, 0.01 in.	10	--	7	10	5	4	5	7	7	9	9	8
Bulk Sp. Gr.	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	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, %	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, %	33.8	37.7	37.3	35.0	22.3	23.1	24.5	25.0	25.1	26.3	28.0	28.1

Aggregate	B-7				B-8				B-9	B-10	B-11
Material	10% B1 90% B6				20% B1 80% B2				30% B1 70% B2	40% B1 60% B2	20% B1 80% B3
Mix No.	FA3B7	FA4B7	FA5B7	FA6B7	FA4B8	FA5B8	FA6B8	FA7B8	FA4B9	FA4B10	FA4B11
Asphalt Content, %	3.0	4.4	5.2	5.6	4.0	4.8	5.7	6.4	4.4	4.3	4.1
Mixing m.c., %	6.5	6.6	6.7	6.9	5.8	6.6	7.8	6.2	7.7	7.7	7.9
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
Marshall Stability, lb	77	580	1393	1620	4468	3173	3030	2329	3002	2540	204
Flow, 0.01 in.	13	8	5	5	7	7	7	8	8	8	8
Immersion Stability, lb	0	77	130	160	1383	1340	1134	861	-	-	-
Flow, 0.01 in.	-	7	8	8	8	9	8	10	-	-	-
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
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
Air Voids, %	28.5	24.6	23.6	22.9	13.6	13.1	13.7	13.6	13.6	7.5	11.4
VMA, %	33.8	32.3	32.8	34.3	21.9	22.9	24.9	26.1	22.6	16.1	19.2

Aggregate	C-1				C-2			
Material	Story Co. Road Top Material (Crushed stone)				Shelby Co. Road Top Material (Crushed stone)			
Mix No.	FA3C1	FA4C1	FA5C1	FA6C1	FA3C2	FA4C2	FA5C2	FA6C2
Asphalt Content, %	2.9	4.2	5.0	6.2	3.2	4.0	5.3	6.0
Mixing m.c., %	7.5	8.9	8.7	5.2	5.6	5.9	6.5	5.8
Cured m.c., %	1.2	3.8	3.9	0.4	1.1	1.3	2.0	1.5
Marshall Stability, lb	0	252	467	445	1636	2891	2551	1558
Flow, 0.01 in.	-	12	21	20	10	9	11	12
Immersion Stability, lb	0	0	0	0	83	494	655	278
Flow, 0.01 in.	-	-	-	-	11	20	15	25
Bulk Sp. Gr.	1.944	1.951	1.969	1.909	2.141	2.139	2.133	2.083
Unit Wt. pcf	121.3	121.7	122.9	119.1	133.3	133.4	133.1	129.9
Air Voids, %	21.2	19.4	17.8	19.1	12.4	11.5	10.3	11.5
VMA, %	26.7	27.4	27.3	30.2	19.1	19.6	20.9	23.4

Note:
1 lb = 0.004448 kN
1 in. = 25.4 mm
1 pcf = 16.02 kg/m^3

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 F, wet	0	1010	357	---	1307	520	1967	---	---
77 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	30	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	109	7	113	70	18	194	0	25
Based on c and Φ	---	341	674	482	2846	552	1931	467	1039

* AC-10

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

*** 1 lb = 0.004448 kN

Loess (B-1): Figure 6 shows the effect of adding 4.4 to 9.5 percent foamed asphalt to this plastic loess on Marshall properties. Both standard stability and unit weight peaked at about 7.3 percent of asphalt. Although the foamed mix at this asphalt content met stability and flow criteria for hot mix, the specimens collapsed upon immersion in water at 60 C 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 four percent asphalt shrank to the extent that the K-test could not be performed.

Pit-run Sand (B-2): Figure 7 shows the Marshall properties of this material stabilized with foamed asphalt between three and five percent. Maximum stability and unit weight occurred at four percent asphalt. However, flow values were low and erratic. Hubbard-Field stability (1 hr at 60 C) at 4.3 percent asphalt showed 4.5 kN and an absorption value of 0.4 percent (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 1.9 kN (at five percent A.C.). The mixing moisture content of seven percent was identical to the amount used for B-2. The freeze-thaw resistance of Csanyi's road sand mix was considered excellent.

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 percent were blended with pit-run sand and mixed with foamed asphalt. Figure 8 shows the Marshall properties of foamed mixes at four to six percent A.C. using 20 percent loess and 80 percent sand (B-8). The results were drastically increased unit weights, 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 four percent asphalt were plotted against blending ratio in Figure 9. Although as much as 40 percent loess

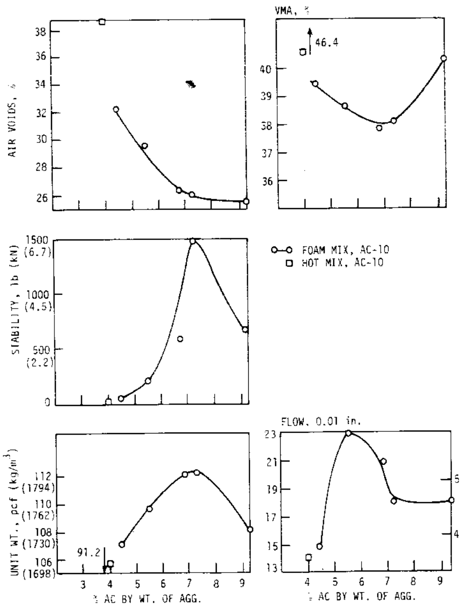

Fig. 6. Marshall Property Curves of Foamed Asphalt Mixes Using B-1 with AC-10.

could be blended with sand to produce acceptable mix (B-10), the optimum ratio for stability appears to be 20 percent loess and 80 percent sand (B-8). At 20 percent loess the percent passing No. 200 sieve was about 24 percent; at 40 percent loess the percent passing No. 200 sieve was 43 percent.

A foamed asphalt stabilized plant mix using materials similar to B-8 was tested by Csanyi in 1956 (*3*) on a pavement carrying 400 cars per day. The

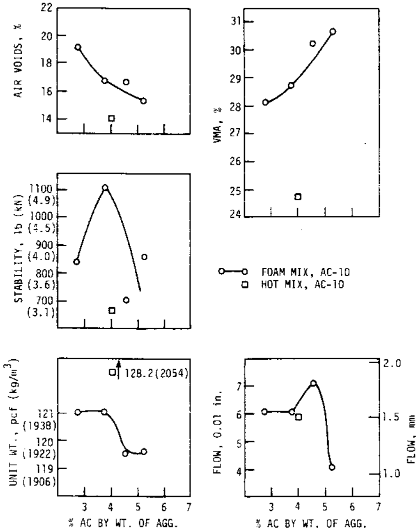

Fig. 7. Marshall Property Curves of Foamed Asphalt Mixes Using B-2 with AC-10.

soil mixture was a blend of 75 percent fine sand and 25 percent loess. Six percent foamed asphalt (150/200 pen.) was added to the moist (eight percent 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 six percent foamed asphalt had Marshall stability of 4.9 kN compared to about 13.3

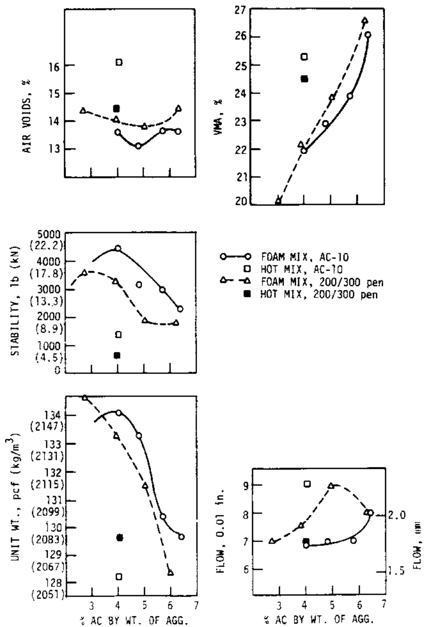

Fig. 8. Marshall Property Curves of Foamed Asphalt Mixes Using B-8.

kN for B-8; Csanyi's mix had a standard Hubbard-Field stability of 2.8 kN compared to B-8 at four percent A.C. of about 8.9 kN. 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 ratio (B-8) and at four percent foamed asphalt are given in Table 4. The Hubbard-Field stability of 8.7 kN and Hveem stability of 31 met both design criteria for hot mix base and light traffic surface course.

Poweshiek Co. Blow Sand (B-3): Figure 10 shows Marshall properties of B-3 mixes at three to six percent 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. This unusual behavior was reflected in the compacted densities. The Hubbard-Field and Hveem stabilities were also low. Several fine sands could be found in Csanyi's report that were similar to B-3 except that they contained five to ten percent less passing No. 200 sieve. A Minnesota sand produced foamed mixes at four to six percent asphalt with Hubbard-Field stability in the range of 0.8-2.8 kN tested at 60 C wet, as compared to 1.6 kN 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 (*3*).

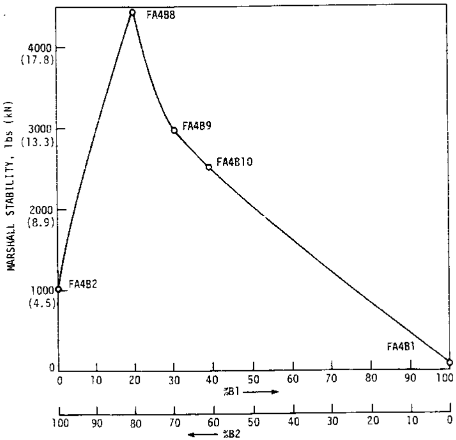

Fig. 9. Marshall Stability of Pit-Run Sand (B-2) Blended with Varying Percent of Loess (B-1)—4 Percent Foamed Asphalt AC-10.

One foamed asphalt project using a fine sand almost identical to B-3 involved the base stabilization of 36 hectares (90 acres) of parking lot of the baseball and football stadium in Minneapolis, Minnesota in the spring of 1961. In this project 4.5 percent of a 220 pen. foamed asphalt cement was added to the fine sand containing eight percent moisture. This mix yielded a Hubbard-Field stability of about 15.6 kN at 60 C dry and a moisture absorption of less than 1.5 percent. A comparable mix at 4.5 percent of 200/300 pen. foamed asphalt also at eight percent mixing moisture (Fig. 10) for B-3 gave a Marshall stability of 3.3 kN. After three years, the parking lot required practically no maintenance and had served excellently (*6*).

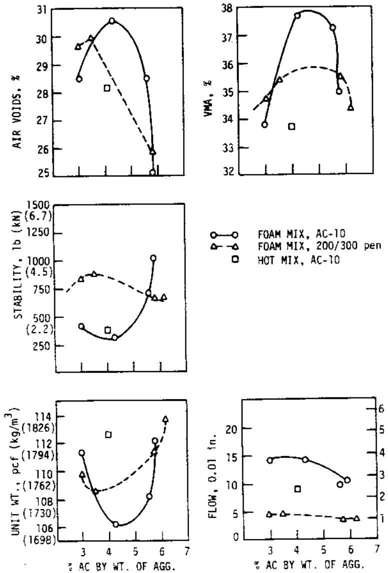

Fig. 10. Marshall Property Curves of Foamed Asphalt Mixes Using B-3.

It was noted that during construction the temperature seldom exceeded 13 C, and work continued daily even when temperatures were as low as 4 C and during light showers.

Pit-run Gravel (B-4): Figure 11 shows the Marshall properties at foamed mixes using the pit-run gravel with AC-10 at three to six percent range. Both stability and unit weight peaked at four percent asphalt. Flow values were low and not much influenced by asphalt content change. Marshall stability of 6.2 kN and Hveem stability of 39 met stability requirements for hot mixes.

Although a number of tests were conducted by Csanyi (*3*, *6*) 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 four to five percent of 125 pen. foamed asphalt, these mixes had a Hveem stability of 23-33. They were laid as a surface course on a lightly travelled road in Maricopa County, Arizona, in 1960. Initial performance of the 50 mm surfacing was "functioning satisfactorily under traffic." There is no record of long term performance.

Limestone Crusher Waste (B-5): Figure 12 shows Marshall properties of foamed mixes using a crusher waste material from Black Hawk Co. at four to seven percent asphalt. This material produced foamed mixes of high stability (6.2-12.5 kN) and low but acceptable flow value of 2 mm. At 4.4 percent asphalt the foamed mix had a Hubbard-Field stability of 5.8 kN and Hveem stability of 62.

Csanyi reported test results of only two crusher waste materials for adaptability to stabilization by the foamed asphalt process (*6*). The two materials were identified as crusher waste and stone dust from Maine. The stone dust was somewhat like B-5 except for having nine percent passing

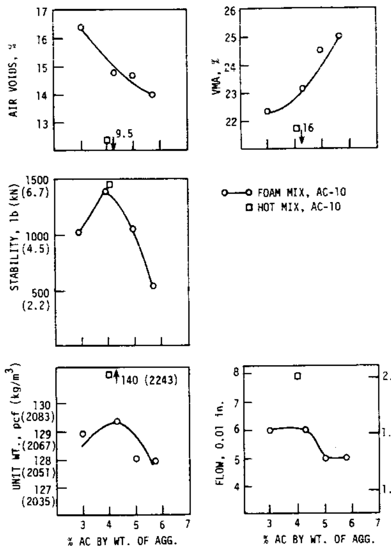

Fig. 11. Marshall Property Curves of Foamed Asphalt Mixes B-4 with AC-10.

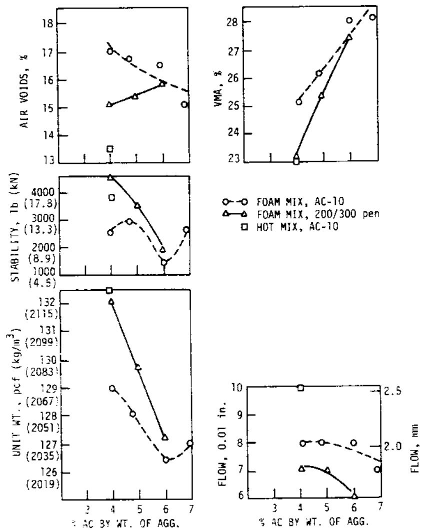

Fig. 12. Marshall Property Curves of Foamed Asphalt Mixes Using Crusher Waste (B-5).

the No. 200 sieve while 29 percent of B-5 passed through. The Maine crusher waste was a much coarser material than B-5. At six percent foamed asphalt the stone dust had a Hubbard-Field stability (60 C, wet) of 3.7 kN compared to 5.8 kN for B-5. The Maine crusher waste had a Marshall stability at 60 C of 2.1 kN compared to 11.0 kN for B-5 at four percent asphalt. Both of the Maine materials were considered suitable for base construction by the foamed asphalt process.

Shelby Co. Blow Sand (B-6): The optimum asphalt content for B-6 using foamed 200/300 pen. asphalt was found to be at three percent. The Marshall stability at this asphalt content was 2.3 kN (520 lb). The Marshall properties of foamed mixes using this sand blended with ten percent loess (B-7) and AC-10 are shown in Figure 13.

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 percent passing No. 200 sieve whereas the other two materials contained four to seven percent passing No. 200 sieve. At five percent foamed asphalt the Minnesota sand and the South Carolina beach sand had standard Hubbard-Field stabilities of 2.0 kN and 2.7 kN respectively; at similar asphalt and mixing moisture content B-7 had a comparable stability of 2.3 kN.

One field project worth mentioning here was that of stabilization of 2.4 hectares (6 acres) of 152 mm (6 in.) base for a parking lot in Sioux City, Iowa in 1959 (*3*). In this project in-place loess (almost identical to B-1) was blended with 33 percent locally available river sand (almost identical to B-6). The blend was stabilized with six percent foamed asphalt. The stabilized mix gave a standard Hubbard-Field stability of 1.8 kN and satisfactory resistance to freezing and thawing. Observations after one severe

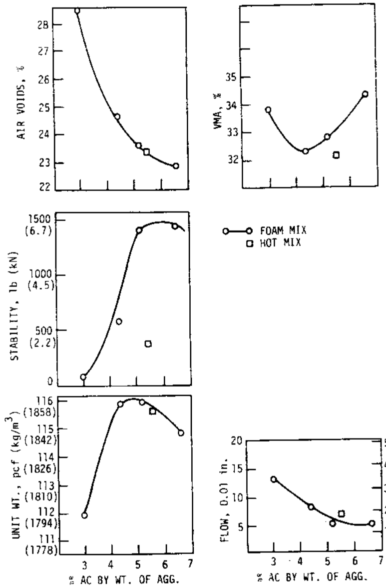

Fig. 13. Marshall Property Curves of Foamed Asphalt Mixes Using 90 Percent Blow Sand (B-6) Blended with 10 Percent Loess (B-1) with AC-10.

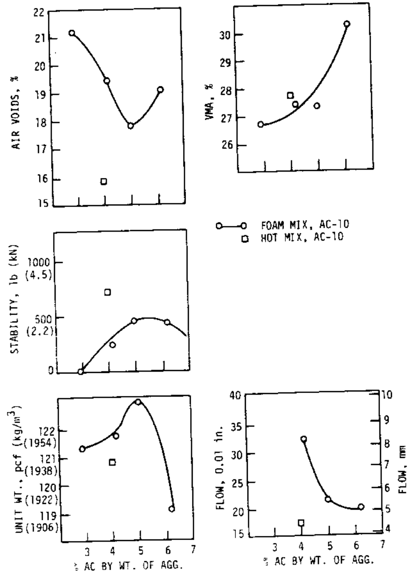

Fig. 14. Marshall Properties of Foamed Asphalt Mixes Using Story Co. Road Surface Material (C-1) with AC-10.

winter indicated that the parking area was in excellent condition. Of special interest is that the blended material in this project contained about 65 percent passing the No. 200 sieve.

Story Co. Road Surface Material (C-1): Figure 14 shows the Marshall properties of this material at three to six percent foamed asphalt. Both stability and unit weight peaked at five percent asphalt cement. At this asphalt content the Marshall stability was 2.2 kN and flow was 5.3 mm. Marshall specimens at all asphalt contents collapsed after immersion in water at 60 C 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 (*3*). Soils in the top 150 mm of materials to be processed were predominantly A-6 (5) with a plasticity index of about 14, much like C-1. Five percent of foamed asphalt was added to the material containing nine percent moisture. Tests performed on the cores taken from the 4-in. compacted base showed a Marshall stability of 1.9 kN, 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.

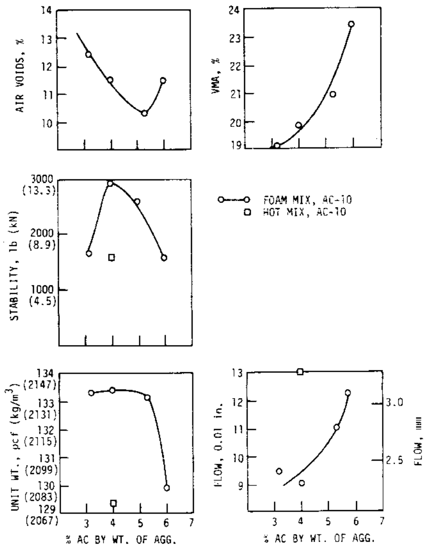

Fig. 15. Marshall Properties of Foamed Asphalt Mixes Using Shelby Co. Road Surface Material (C-2) with AC-10.

<u>Shelby Co. Road Surface Material (C-2)</u>: Figure 15 shows the Marshall properties of foamed mixes using this material at asphalt contents in the three to six percent range. The curves show trends similar to hot mixes. At four percent foamed asphalt the mix yielded an excellent stability of 12.9 kN and flow of 2.3 mm, both meeting standard criteria for hot mix. The mix also showed excellent resistance to water damage with an immersion stability of 2.2 kN.

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 as a heavily travelled base, as county road surface with a light application of seal coat or, possibly as a county road surface after the coarse particles over 19 mm (3/4 in.) in size were removed.

Based on the Mohr theory of the strength of a confined specimen, both Metcalf (*15*) 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:

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

Using this equation, bearing capacities of foamed mixes in Series A at approximately four percent 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 60 C, to 4964 kPa for B-8 at standard Marshall condition.

To perform satisfactorily as a surface without excessive plastic deformation, a pavement mixture should have a minimum bearing capacity of 690 kPa, the maximum loading imposed by truck tires. 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 range from 2.4 MPa for B-2 to 19.6 MPa 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 60 C 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 (*17*). 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 24 C, approximately the temperature at which the Iowa K-tests were conducted.

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 four percent asphalt content and tested for Marshall properties. The results of these are given, together with corresponding foamed mixes, in Table 5. The following can be observed:

Table 5. 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	Emulsion	Hot	Foam	Foam	Hot	Foam	Foam
Mix No.	HA4B1	FA4B1	HA4B2	FA4B2	HA4B3	FA4B3	FP4B3	E6B3	HA4B4	FA4B4	FP4B4	HA4B5	FA4B5	FP4B5
Asphalt Type[1]	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	6.0	4.3	3.5	4.0[2]	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[3]	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	866	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	5	18	-	-	-	9	4	-	18	7	-
Marshall Stability at 77°F, lb	-	-	-	2964	-	3106	-	-	-	-	-	-	8256	-
Flow @ 77°F	-	-	-	7	-	5	-	-	-	-	-	-	10	-

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.	HP4B6	FP4B6	HA5B7	FA5B7	FP5B7	HA4B8	FA4B8	HP4B8	FP4B8	HA4C1	FA4C1	E6C1	HA4C2	FA4C2	E6C2
Asphalt Type[1]	P	P	A	A	P	A	A	P	P	A	A	E	A	A	E
A.C. by wt of Aggregate, %	4.0	4.1	5.5	5.2	5.5	4.0	4.0	6.0	3.9	4.0	4.2	4.0[2]	4.0	4.1	4.0[2]
Mixing m.c., %	0	9.6	0	6.6	7.2	0	6.8	0	7.4	0	8.9	11.5[3]	0	5.9	6.6[3]
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	-

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

[2] Residue asphalt content

[3] Including water in emulsion

Note:
1 lb = 0.004448 kN
1 in. = 25.4 mm
1 pcf = 16.02 kg/m^3

- 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 a higher stability value than the corresponding foamed mix. For the crusher waste (B-5), the hot mix had a higher stability than the foamed mix made with AC-10 but lower than the foamed mix made with 200/300 pen. asphalt.
- 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 better coating of coarse particles and harder base asphalt used in the emulsion (CSS-1h), all three emulsion mixes produced Marshall specimens with higher densities and stabilities than corresponding hot and foamed mixes.

Effect of Mixing Moisture Content

Both Professor Csanyi's original work on foamed asphalt soil stabilization (*3*, *18*) and recent studies in Australia (*8*, *19*, *20*) showed the need for mixing water in the soil-aggregate before the addition of foamed asphalt. In Csanyi's experiments this ranged from about six to ten percent. Concerning the required water in the soil aggregate, Csanyi wrote (*3*):

> "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 percent of optimum.

Recent studies by Mobil Oil of Australia (*8*) 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 percent of optimum moisture content as determined by AASHTO T99 (*12*, *21*).

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 three to four percent asphalt cement at ranges of moisture content from near zero to about 100 percent of optimum moisture content. The results are given in Table 6. The Marshall stability versus mixing moisture content curves are shown in Figure 16. 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 percent for B-4 (pit-run gravel) to about 10.5 percent for B-3 (pit-run sand), corresponding to about 65 to 85 percent of optimum moisture content (AASHTO T99) for each aggregate.

Table 6. Effect of Mixing Moisture Content (200/300 Pen.)

Aggregate	B-3								B-4					
Asphalt Content, %	4.1	3.5	4.0	3.9	2.9	2.9	2.9	3.2	4.0	3.9	4.2	4.1	3.9	4.1
Mixing m.c., %	5.4	8.1	9.9	12.1	7.0	9.2	11.1	12.8	0.3	2.7	5.0	6.5	8.4	5.7
% of OMC	43	65	80	97	56	74	89	102	4	33	61	80	102	70
Compaction m.c. (as % of OMC)	43	65	80	97	56	74	89	102	30	33	61	80	102	100
Cured m.c., %	0.1	0	0.3	0.4	0.1	0.4	0.3	0.5	1.4	0	0.2	0.3	2.0	2.7
Marshall Stability, lb	461	857	948	894	35	1396	2157	1889	83	559	1006	1021	716	384
Flow, 0.01 in.	4	6	4	7	5	5	5	7	5	4	5	5	9	7
Bulk Sp. Gr.	1.78	1.74	1.78	1.83	1.747	1.775	1.790	1.767	1.77	2.11	2.15	2.18	2.15	2.12
Unit wt. pcf	111.1	108.6	110.5	113.9	109.0	110.5	111.7	110.3	110.3	131.3	136.0	135.7	134.0	132.4

Aggregate	B-5			B-7				
Asphalt Content, %	3.7	4.0	4.1	3.5	3.8	4.1	3.8	4.7
Mixing m.c., %	5.8	7.8	10.1	5.5	7.9	9.5	11.0	7.7
% of OMC	48	65	84	50	70	86	100	70
Compaction m.c. (as % of OMC)	48	65	84	50	70	86	100	100
Cured m.c., %	0.2	0.4	0.2	0.7	0.4	0.4	0.5	0.4
Marshall Stability, lb	565	4396	2523	767	1783	1900	1539	1142
Flow, 0.01 in.	6	7	10	4	5	4	5	5
Bulk Sp. Gr.	2.05	2.12	2.07	1.86	1.89	1.91	1.87	1.87
Unit wt. pcf	127.6	132.0	129.1	115.8	118.4	119.0	116.9	116.9

Note:
1 lb = 0.00448 kN
1 in. = 25.4 mm

Since the optimum mixing moisture content occurs at 65 to 85 percent of optimum compaction moisture content, a question arose as to the desirability of mixing at a moisture content 20 to 30 percent 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 percent of optimum. Water was then added to the mixes bringint 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 mixes mixed and compacted at 70 to 80 percent of optimum moisture content and also below those of the equivalent mixes

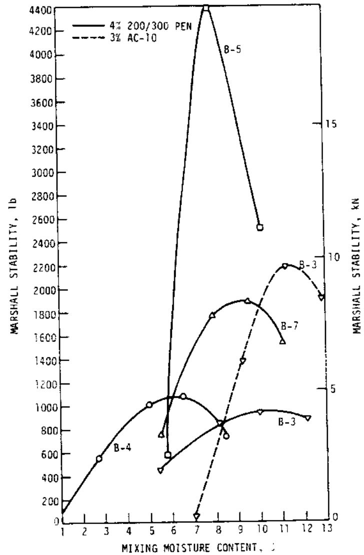

Fig. 16. Effect of Mixing Moisture Content on Marshall Stability.

mixed and compacted at the same level of 100 percent optimum compaction moisture content.

To investigate the effect of additional moisture after foamed asphalt is made on the Marshall properties at extreme dry conditions, a foamed mix at four percent asphalt was prepared using B-4 at natural moisture content of about 0.3 percent. The foamed mix was spotty in appearance. 2.1 percent moisture was added to the foamed mix (lowest moisture content that could be molded) making total moisture content of about 30 percent of optimum determined by AASHTO T99. The resulted Marshall stability was 0.4 kN, compared to 2.5 kN obtained from a similar foamed mix (B-4 at 3.9 percent asphalt) but mixed and compacted at about the same total moisture content of about 30 percent optimum.

To summarize, data from 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 percent 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.

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.

Two curing conditions were used by Professor Csanyi (*4*): an air cure at room temperature for three days for mixes to be laid in cool weather and a warm cure at 48.9 C (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 (*22*) suggested that specimens be oven cured while in molds for three days at 60 C (140 F) prior to testing. Laboratory studies performed in Colorado (*12*) used three types of curing conditions: three days at room temperature, one day at 60 C and three days at 60 C.

Because of the limited time and number of molds available, the standard curing condition during this project was three days at 60 C 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 four percent asphalt (200/300 pen.). In this series, foamed mixes were mixed and compacted at about eight percent moisture. Duplicate specimens were cured at room temperature (25 C) and 60 C, both in and out of molds, for various periods of time. Cured moisture contents, standard Marshall stability and flow were determined. The results are plotted in Figure 17. 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.
- At least for this particular aggregate, there appeared to be a critical moisture content above which no Marshall stability was developed.

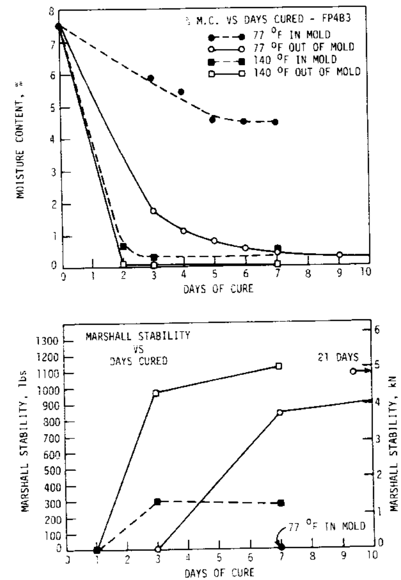

Fig. 17. Effect of Curing Conditions on Moisture Content and Stability.

One may question whether curing at 60 C (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. One may also argue that, for mix design and evaluation purposes, laboratory 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.

Effects of Half-Life and Foam Ratio

Professor Csanyi (*3*) performed an 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 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 (*10, 21*). All foamed mixes made in this study were within these limits as determined by a 3.8-liter (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 four percent asphalt were made at a half-life range of 11 to 136 sec and a foam ratio range of five to twenty. Mixing moisture content was controlled at 70 to 80 percent of optimum for compaction of aggregate by AASHTO T99. Marshall specimens were molded, cured and tested. The results are given in Table 7.

Examination of the data revealed no significant trends. There were essentially no differences between mixes of high and low foam ratios (five versus twenty) 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 hr immersion at 60 C) was made with foam of 18-sec half-life and foam ratio of 15.

CBR of Foamed Mixes

The CBR test was performed on three aggregates (B-1, B-4 and B-8) at about four percent foamed asphalt and ranges of mixing moisture content. The results are given in Table 8. For loess soil (B-1), there was little improvement at low mixing moisture content. When mixing moisture content was increased to 77 percent of optimum, the CBR value increased from three to eleven, about the level of improvement reported by Nady and Csanyi (*18*). Similarly there was no improvement in CBR for the pit-run gravel (B-4) which had a high CBR value without treatment. Foamed asphalt mixes for B-8 (20 percent loess, 80 percent sand) showed the most significant improvement. When mixed and compacted at about 75 percent of optimum moisture content, the CBR of the foamed mixes increased by 10-fold after three days curing and increased from about two to 108 after seven days curing.

Freeze and Thaw Tests

One hot mix and one foamed mix, both at four percent asphalt of AC-10, were prepared for each of three aggregates: C-1 (Story Co. road

Table 7. 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

Note:
1 lb = 0.004448 kN
1 in. = 25.4 mm
1 pcf = 16.02 kg/m^3

Table 8. 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	7.2	4.8		5.8	10.1	6.6	7.4		7.6
(% of OMC)	100	55	60		77	100	88	59		71	100	65	73		75
As molded wet density, pcf	126.1	105.7	110.9		125.4	152.7	144.0	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	134.4	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	-	137.6	134.5	129.0	136.1	-	128.6	132.0	128.8	136.1
Cured m.c. %	-	8.1	6.7	3.0	10.2	-	2.4	1.3	0.4	2.9	-	4.3	2.9	0.9	3.8
CBR, %	3	2	4	4	11	46	36	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.

Note:
1 pcf = 16.02 kg/m^3

material), B-6 (blow sand) and B-8 (20 percent loess blend with 80 percent sand). Three Marshall specimens were compacted from each batch. After three-days' curing at 60 C for foamed specimens, they were exposed to ASTM C666 Method B rapid freezing in air and thawing in water cycles. Eight 4.4 to -17.8 to 4.4 C 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 9. Evidence from these limited results indicated that foamed mixtures were as resistant to freezing and thawing recycles as were hot mixes.

Table 9. 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

Note:

1 lb = 0.004448 kN

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 percent asphalt from a 1979 Kossuth Co., Iowa, recycling project and a salvaged asphalt concrete surface and binder course mixture from I-80 stockpiled in Stuart, Iowa, containing 5.2 percent 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 containing 40 percent virgin aggregate, reasonable mixing and coating was obtained when moisture content was increased to five percent. For the Stuart stockpile material containing 35 percent virgin aggregate, moisture contents beyond two percent (up to six percent) did not improve the mixing and coating. The Marshall stability of foamed recycled mix of Stuart material was

Table 10. Foamed Asphalt Recycling (Kossuth Co.)

Salvaged Material, %	100	80	60	60	60	60	60*
Type of Virgin Agg	--	Crushed Gravel	Blow Sand	← Crushed Gravel →			
Virgin Agg., %	0	20	40	40	40	40	40
A.C. Type	← AC-10 →			← 200/300 pen →			
Added A.C., %	3.2	3.2	3.0	4.0	4.1	4.1	4.0
Total A.C., %	5.2	4.8	4.2	5.2	5.3	5.3	5.2
Moisture added, %	5.0	5.0	5.0	0	3	5	0
Total m.c. content, %	8.6	8.6	7.5	2.7	5.9	7.6	0
Cured m.c., %	1.4	1.7	0.8	0.5	1.1	1.4	0
Marshall Stability, lb.	1407	1115	1043	85	770	864	1394
Flow, 0.01 in.	18	17	8	15	10	12	12
Unit wt. pcf	127.0	127.9	120.9	120.2	126.0	128.5	141.9

*Hot mix

Note:

1 lb = 0.004448 kN

1 in. = 25.4 mm

1 pcf = 16.02 kg/m^3

0.8 kN (175 lb) compared to 9.7 kN (2183 lb) of equivalent hot recycled mix. However, cold recycling using 100 percent salvaged material produced a foamed mix having Marshall stability comparable to that of hot recycled mix at the same total asphalt content. Table 10 gives the results of foam recycled cold mixes as well as the comparable hot recycled mix for Kossuth Co. material.

SUMMARY AND CONCLUSIONS

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

1. Of eight basic materials tested, seven can be designed by foamed asphalt process to meet either Hubbard-Field or Marshall criteria as suggested by Professor Csanyi. Although gradation of sand is not critical to stabilization by foamed asphalt, addition of small amounts of fines (ten to twenty percent) to clean sand greatly improved the stability of the foamed mixes.
2. No apparent differences could be detected between Csanyi's steam foamed asphalt and asphalt foamed by Mobil's cold water process.
3. 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.

4. The optimum mixing moisture content varies with types of materials (percent passing No. 200 sieve), ranging from 65 percent to 85 percent of optimum moisture content determined by AASHTO T99.
5. 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.
6. Although materials containing as much as 65 percent passing No. 200 sieve have been successfully stabilized by foamed asphalt, the realistic upper limit of percent passing No. 200 sieve is perhaps in the range of 35 to 40 percent. 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.
7. While no curing is required before compaction, foamed asphalt stabilized mixes do need curing to improve coating and do develop strength.
8. Within a 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.
9. Cold mix recycling by foamed asphalt process is feasible provided that the mix is based on cold mix recycling concept.
10. 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.

ACKNOWLEDGMENT

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Discussion

MR. S. M. ACOTT (Prepared Discussion): I was fortunate to obtain a copy of Prof. Lee's paper prior to the conference and I would like to congratulate him on a very thorough and interesting investigation.

In Southern Africa, the major efforts using the foaming technique have been on the stabilization of natural sands. Treatment has been carried out in both drum and batch mixers, and also in situ using a converted pulvimixer. In all cases, the system used has been the water generated foam process. Several experimental pavements have now been constructed and although these pavements are only 2-4 years old, initial performance data is very encouaging. In most cases the structures are comprised of a surface treatment then a 150 mm foam stabilized sand base on sand subgrade. Traffic has been up to 50 equivalent standard axles.

Several interesting points have been raised by Prof. Lee, and I would just like to make some brief comments on his findings.

1. The high Marshall stabilities for foam specimens is in line with our observations, although we evaluated stability using other test methods. We reasoned that these high strengths were due to the unique structure of mix. In the foam mixtures there is direct intergranular contact, whereas if the binder evenly coated the particles this could reduce ϕ and enable shear to take place at a lower dilation. In your Iowa K test device did you compare c and ϕ values for foam treated specimens and other mix types?
2. You evaluated the after soak stabilities using the Marshall Immersion stability test do you believe that for base or subbase stabilization, test methods that are used for evaluating liquid asphalt mixtures are possibly more appropriate? I am thinking along the lines of the stabilometer and MVS test conditions, we also have had some success with a vane shear apparatus.
3. Your study shows that maximum shear strength does not occur at maximum dry density and that it would be worthwhile to evaluate mixing moisture content as part of the design method. I would also like to add that for inherently unstable sands the workability of the mix must also be considered, when you are working on the dry side of optimum, some mixtures can become very harsh and friable and possibly develop fine roller cracks, or material pick up under the rollers. Possibly a compromise must be reached between density and shear strength. A denser mix may also assist the after soak stabilities.
4. Finally, I would like to comment on the curing of foam treated materials. In our field studies we have witnessed a steady increase in shear strength over a 3-year period. For some mixtures vane shear strengths have, for example, increased by over ten-fold. Other researchers have also observed this increase in strength for both emulsion and cutback treated materials, so this time hardening is not restricted to foam treated mixtures. The problem as we see it, is the selection of the appropriate cure conditions, ensuring adequate shear strength in early life, and selecting the right stiffness for structural design reasons. The various design models are available to take into account this strength increase, but as you rightly state more information is required on the curing aspect. Your planned laboratory-field curing correlation is therefore of great interest.

PROFESSOR D. Y. LEE: Let's see if I remember all the points. No. 1 is the K-test. Actually the last two slides which I did not have time to talk about were about the K-test. This test was developed by our soils group making use of the standard Proctor sample. This is the 4-in. diameter sample confined in a spring loaded ring. We apply vertical load, the split steel mold provides a measure of lateral displacement and stress. From there you can produce, from one single sample, a continuous plot of σ_1 versus σ_3 or the p versus q curve. In deriving c and ϕ values, you use a linear

regression to fit the p-q plot and convert slope and intercept to ϕ and c. The sample was loaded at a loading rate of 0.05 in./min. We had just one sample that could not be tested, that was the loess; because after it's cured the loess shrinks and therefore we were not getting the true stress ratio, k, or σ_3 over σ_1. The c and ϕ values were reported in the paper. The cohesion values varied from 11 to 62 psi and ϕ angle derived from this device varied from 27 to 44 degrees. We plotted our data on the old Smith triaxial design criteria chart (*17*), and all our samples except the loess fell within the area that is considered to be "satisfactory." The K-test was performed at room temperature and the Smith triaxial criteria was based on room temperature.

On the selection of appropriate curing conditions, we cured samples both at room temperatures and at 140 F, both inside the mold and outside the mold, for up to 28 days. Our data show that how you cure the sample is really not that important. At approximately equal cured moisture content you would have about the same stability. No. 3, on the use of the Marshall immersion compression test to evaluate the water susceptibility. I agree, I'm not sure that it might not be too severe. We are looking at this question. We have generated more data since this paper was written. We have since used the vacuum saturation method to compare various curing conditions including vacuum desiccation. However, it does cause concern that, in five out of six comparisons, foamed mixes had lower retained strength based on Marshall immersion.

MR. L. D. COYNE: I was particularly interested in comparing foamed asphalt with hot mix. As the author points out the wet strength of foamed asphalt is less than hot mixes. My question is why? I believe poor densities are the reason. Only your C_2 material had higher density with foamed asphalt. This is the only mix which looked better in wet strength compared to hot mix. Foamed asphalt mixes appear to be extremely sensitive to moisture in both coating and density. I believe this is one of the major weaknesses of the foam system.

PROFESSOR LEE: I agree that moisture content is extremely sensitive in coating and density. Most of the foamed mixes performed not as well as the hot mix based on the Marshall immersion, although based on the standard Marshall, in 9 out of 11 comparisons the foams performed better. Of course on the premises that you can use Marshall immersion as a criterion.

ELAINE THOMPSON: Professor Lee, it seems to me that what you have is very similar to an unstable inverted emulsion. One would expect that a water-in-oil emulsion (in other words an inverted emulsion) should have effects very similar to those that you see with foamed asphalt and marginal aggregates. Have you ever made that comparison?

PROFESSOR LEE: I have to think about this. You ask me whether we have an inverted emulsion. I know what an inverted emulsion is, but I have not made such a comparison.

MR. W. J. KARI: It's a cutback in which you incorporate water and adhesion agents.

MR. R. E. ROOT: Dr. Lee, I question whether we actually have coating of the fine aggregates like so many people are discussing. I'm wondering if we have more of a system of asphalt globules between the aggregate particles and when you put the materials in an oven then you get a coating on it. So I'm questioning do we really get coating of the fine aggregates in the mixing process?

PROFESSOR LEE: You may have heard that Professor Csanyi has referred to this as a mortar theory. His field tests showed that initially there might not be coating on all the fine particles, but with time and traffic kneading action the fines were coated in time.

MR. ROOT: The system that I have seen is the water system and not the steam so I don't know whether the steam system provided coating or not, but it looks like the water system of foaming asphalt does not coat the fine particles, during the mixing operation.

PROFESSOR LEE: We did look at some of the particles under a microscope after they were cured in lab condition. Of course the large particles, larger than 1/4 in., are not completely coated. But the finer ones we couldn't tell the difference between foamed mixes and the hot mixes. Is Bob Nady here? Of course as you know he was instrumental in Professor Csanyi's work. Bob may have something to say about this.

MR. R. M. NADY: Just one brief one Dah-Yinn and thank you. Back in the days when air was clean and sex was dirty, to paraphase Barney Vallerga, the reason we used steam in the original foam development back in the mid 50's was the fact that in those days all the asphalt plants had a steam jetty to keep the asphalt warm, to keep the piping jacketing on the piping system, and the pugmills all warm. That was one reason you always had steam around in asphalt plants. So why not use it to foam the asphalt? That was one of the concepts. In regard to the coating problem, I can remember Professor Csanyi also using this same illustration. If you ever stick your finger into the soap bubble, the same thing happens when an aggregate particle finds itself stuck into a foamed asphalt bubble, I think. You get some initial coating. Some of this might be over, however, a water film around the particle. So I think the fines do, initially pick up some coating of asphalt when the foam process is used, but it's difficult to see the asphalt in the mix. It does change color with age as traffic and curing occur, further distributes the asphalt through the mix. I think it is important, however, that the fines, which are very sensitive and very important to the strength of asphalt mixes, whether it's a surface or base mix, wherever it is in the pavement system, do pick up the coatings fairly often.

MR. ROOT: I have one more question. Dah-Yinn, most of the moisture damage tests have been done on oven-cured specimens and I would question whether the retained strengths would be as good on air-cured

specimens and maybe suggest that you'd have drastic loss of strengths due to moisture damage in that situation.

PROFESSOR LEE: I suspect that you might be right. We are continuing the moisture damage tests. We're going to use the resilient modulus for the non-destructive testing and we're looking at vacuum saturation under different curing conditions. An important consideration in assessing foamed mix suitability is the selection of appropriate lab curing conditions. I don't recall now whether I mentioned Professor Csanyi's curing conditions. He had two. He had one called cool weather curing: air curing at 77 F room temperature for three days. If it is to be used in a warmer climate he used warm cure: 120 F for three days. He had design criteria based on both. Apparently he had verified these by his experiences.

AUTHOR'S CLOSURE: Questions raised during the oral discussion centered mainly on two areas: coating of fine particles and water-susceptibility of the foamed mixes versus curing conditions. In view of new data obtained since the preparation of the paper, I wish to expand on these aspects of our work.

We have made extensive microscopic examination of air cured foamed mix particles (at 4 percent asphalt) of all materials reported in the paper. We have concluded that for particles finer than about No. 30 sieve (0.6 mm) all particles were completely coated; particles between No. 30 (0.6 mm) and No. 4 (6 mm) were either coated by a very thin film of asphalt or completely surrounded by coated smaller particles forming a mortar; particles larger than No. 4 sieve were largely uncoated. The asphalt film in the No. 4 and No. 30 size range was so thin it could only be detected by comparing with particles of the original aggregate in the same size range side by side.

We also completed a study on water-susceptibility of foamed asphalt mixes of B-4 (A-1-b) and C-2 (A-2-b) materials at 4 percent asphalt and at three levels of prewet moisture content (55, 75 and 100 percent of optimum moisture content) using vacuum-saturation treatment. Curing conditions varied from 77 F (25 C) to 140 F (60 C) and up to 28 days. A special group of Marshall samples (C-2 at 75 percent of optimum moisture content) were cured at 77 F (25 C) in humidity room while wrapped in plastic film to prevent moisture loss. The results in terms of Marshall stability after vacuum-saturation revealed two interesting, if not significant, findings:

1. Although in the majority of cases, curing at 140 F (60 C) resulted in higher Marshall stabilities (after vacuum-saturation) than identical samples cured at 77 F (25 C) to equivalent cured moisture content, there were exceptions. For example, B-4 mixes prepared at moisture contents of 55 to 75 percent of optimum moisture content, had equal or higher vacuum-saturation stabilities when cured at 77 F (60 C) in air than when cured at 140 F (60 C) in oven, compared at equal cured moisture content.

2. Moisture loss was not a necessary condition for foamed asphalt mixes to gain strength. The C-2 mix prepared at prewet moisture content of 75

percent of optimum had higher vacuum-saturation stability both at 7 and 28 days of cure when cured in a humidity room without any moisture loss than identical specimens cured either in air at 77 F (25 C) for the same curing time or in oven at 140 F (60 C) for three days with moisture loss due to evaporation.