1976

sand treated asphalt and traffic volumewise is not very heavy, but weightwise we have some tremendous loads. We have a very good surface life so far we have had four years of traffic on one particular road and the road is holding up very well.

MR. WALKER: May I ask what sort of stability and air void values you had?

PROFESSOR EUGENE L. SKOK: The Marshall stability on that particular mix was very close to zero. We had a hard time catching the mix with the testing machine.especially at 140 F (60 C). Unconfined its a very unstable mix. But once we did get it down in the field it has performed very well. In fact the maximum measured rut depth is on the order of about 0.15 in. (3.8 mm) after 3-1/2 years. The void content ranged from about the 13 to 17 percent which would be within the criteria that you mentioned.

MR. WALKER: That's very interesting.

FOAMED BITUMEN
PRODUCTION AND APPLICATION OF MIXTURES
EVALUATION AND PERFORMANCE OF PAVEMENTS

R. H. BOWERING[1] and C. L. MARTIN[2]

INTRODUCTION

In recent years considerable experience has been gained in Australia with the construction of pavements incorporating foamed bitumen. Development of an improved foaming technique (1) has enabled effective and economical stabilization of marginal quality pavement materials with an improvement in handling and compaction characteristics plus an upgrading of physical properties relevant to service performance. As a result use of foamed bitumen treated crushed rock is finding increasing application as a base course material, used either as complete replacement for granular material or as part replacement for asphaltic concrete.

This paper presents an overview of foamed bitumen technology in which production, testing procedures and properties of foamed bitumen mixtures are discussed. It is shown that the quality of foam is important and that properties of foamed mixtures are different to those of cold mixtures produced with other materials such as emulsions or cutbacks. Laboratory studies on numerous mixtures are reported and layer equivalency values are discussed for those mixtures using measured cohesion values or elastic moduli.

FOAMED BITUMEN PRODUCTION AND INCORPORATION

The production and some uses of foamed bitumen were first described by Csanyi (2, 3). The original process essentially consisted of introducing steam into hot bitumen through a specially designed nozzle such that the bitumen on ejection was temporarily transformed to a foamed condition.

The properties of the foamed bitumen include a low apparent viscosity, substantial increase in surface area and a change in surface or interfacial tension. These properties of the hot foam enable coating of moist, cold aggregate surfaces—particularly the "fines" portion of the material.

The importance of achieving foamed bitumen of desired properties in a consistent fashion is especially significant and an improved production method has been developed by Mobil Oil Australia Limited (1). This improved system involves introduction of a controlled flow of cold water into a hot bitumen stream, mixing in a suitable chamber and

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The oral presentation was made by Dr. Charles Pagen of Mobil Oil Corporation, New York, N.Y.

delivery to a spray bar fitted with fixed aperture nozzles. Given a constant bitumen flow it is necessary to vary only the quantity of water injected in order to control the foam quality, which may be evaluated by sampling at any nozzle during operation. The new method allows precise control and automatically minimizes the possibility of differences in foam quality which can occur with individually adjustable nozzles. In addition to providing a more precise and yet simpler system this new method involves less capital outlay and entirely eliminates the necessity for a steam generating system.

The type of foam found most effective is that having an expanded volume of some 10 to 15 times the volume of hot liquid bitumen which may be produced by injection of between 1 and 2 percent water. Satisfactory foam at this expansion typically takes between two and three minutes to deflate to half its original volume. This combination of expansion and stability allows the foam to be adequately mixed with mineral aggregates using conventional mixing equipment. An example of the properties obtained with one particular material using low expansion foam is shown in Table 1 together with properties obtained with satisfactory foam. The improvement in the latter is particularly marked.

LABORATORY TEST PROCEDURES

Many tests have been used to evaluate the effect of bitumen in the field of soil stabilization (4). It is considered that the ideal evaluation

Table 1. Effect of Foam Quality on Mix Properties

Test		Untreated	Low expansion foam. 3:1	High expansion foam. 15:1
Bitumen content. % 90 pen.		—	2.8	2.8
Dry density.	lb/cu ft.	127	128	130
Resistance Value	— After curing	90	95	96
Resistance Value	— After 4 day soak	Collapsed	75	83
Relative Stability	— After curing	40	51	64
Relative Stability	— After 3 day M.V.S.	18	20	43
Cohesion	— After curing	277	509	709
Cohesion	— After 3 day M.V.S.	Collapsed	48	387
U.C.S.	— After curing, psi	268	648	816
U.C.S.	— After 4 day soak, psi	Collapsed	64	144
Free Swell	— in. x 10^{-3}	19	17	3
Permeability	— ml/24 hrs.	500+	450	210

Untreated Soil Characteristics:

Classification — Sandy loam (SP — SC)

Grading:

Sieve No.	3/8 in.	3/16 in.	7	14	25	36	52	100	200
(mm)	(9.5)	(4.76)	(2.41)	(1.41)	(0.71)	(0.425)	(0.280)	(0.149)	(0.074)
% Passing	100	99	93	75	39	25	17	10	5

P.I. 5

system should measure the mixture's resistance to deformation under vertical loads over ranges of temperatures, loading conditions and moisture contents spanning service conditions. Additionally the cohesion of the compacted mixture and changes with moisture variation should be determined.

A laboratory testing procedure has been developed to essentially meet the above requirements (5). Five tests based on California Division of Highways test procedures are routinely used in mix design assessment. Modifications to standard procedures entail mixing of the foamed bitumen with soil or aggregate at a moisture content near to optimum for compaction of the mixture and at room temperature. Compaction by kneading compactor is carried out on the mix at ambient temperature to simulate field construction. Specimens are oven cured for three days at 60 C (140 F) prior to testing in order to simulate the initial loss of moisture and subsequent gain in strength of the mix during construction and the early part of its service life.

The tests used are:

a. Modified Resistance Value. Conducted at ambient temperature before and after four days soaking in water.
b. Modified Relative Stability. Conducted at 60 C (140 F) before and after three day exposure to moisture vapor.
c. Cohesion. Conducted at 60 C (140 F) before and after three day exposure to moisture vapor.
d. Free Swell and Permeability.
e. Unconfined Compressive Strength. Conducted at ambient temperature before and after four days water soaking.

Study of these methods (6) has shown that alternative procedures such as Marshall or California Bearing Ratio give similar results in terms of mix design when a curing period is included prior to testing, although they may not adequately reflect structural benefits particularly with respect to cohesion. It has also been demonstrated that static test values are usually maximized at a moisture content in the range of 30 to 40 percent of optimum compaction moisture and that curing temperature in the range of ambient to 60 C (140 F) has little or no influence on test results.

In structurally weak soils it is normally found that values for Resistance, Relative Stability, Cohesion and Unconfined Compressive Strength increase to maxima with increasing bitumen content after which they decrease. With bitumen treated crushed rock Relative Stability is generally decreased with increasing permanent Cohesion. Assessment of data obtained from these tests enables choice of a suitable bitumen content for mix design and allows a comparison of the mixture's structural value in relation to standard granular bases or to asphaltic concrete.

It is recognized that static type test procedures do not necessarily provide a consistent means of predicting pavement performance in service. Field observations of pavements constructed with foamed bitumen mixtures (7, 8) have shown satisfactory performance and in particular deflections as measured by a Benkelman beam are comparable with those observed for other types of pavement. Shackel et al (9) have recently shown that for a particular aggregate stabilized with foamed bitumen there is a correlation between static and repeated load testing. It was found that addition of foamed bitumen increased the stiffness of the material under repeated loading by a factor of up to six depending on the moisture content (i.e., degree of moisture saturation), the number of load repetitions and the binder content. The work also showed that maximum resilient moduli were obtained at moisture saturations between 50 and 70 percent for the range of bitumen contents tested, indicating the relevance of a curing period and compaction on the dry side of optimum moisture contents. The ranges of bitumen content and saturation yielding the optimum response in repeated loading were similar to those given by static procedures.

PROPERTIES OF FOAMED BITUMEN MIXTURES

Foamed bitumen may be used to stabilize deficient sands, gravel or fine crushed rock by imparting cohesion and resistance to moisture ingress. At higher binder levels it may also be used to produce bituminous premix without resort to conventional hot-mix equipment, by mixing with cold, moist crushed rock. Thus, the mix properties may be compared on the one hand to untreated or alternate base material and on the other to conventionally produced hot-mix. Which of these is the more applicable depends on the type of untreated material and on the amount of bitumen incorporated. For stabilization, foamed bitumen offers a means of incorporating neat bitumen into moist, cold materials without recourse to prior processing such as emulsification or solvent cutting. Thus the cost of pre-processing and transport of a diluent fraction is eliminated, together with the need for subsequent removal of that fraction by aeration of the mix before compaction. Additionally, there are no environmental problems with evaporation of hydrocarbons as encountered with cutback bitumens.

Foam mixes normally produce fairly stiff, stable mortar type material in which the bitumen is concentrated effectively in the finer fraction of the aggregate, especially in the fine sand and silt fraction. The type of mix usually obtained is similar to that described by Benson and Becker (10) as a "phase-mixture." Mixes handle easily and cleanly in the field and are readily compacted and cured.

It has been shown that there are significant differences between foamed bitumen mixtures and those prepared using a slow setting bitumen emulsion (6). It was found that properties as measured by test procedures described in this paper were similar for both types of mixes up to a level of about 1.5 percent bitumen—with the exception of permeability which was greater for the foam mix. Above this bitumen level the foam mix displayed substantially improved structural properties as typified by Resistance Value, Relative Stability, CBR and

Cohesion. It is believed that the foam system, by concentrating the binder in the fines, results in a stronger mortar fraction than the emulsion method.

Table 2 shows representative test results for a total of 50 materials examined and for convenience they have been categorized into distinct soil types. It may be seen that suitable materials for foamed bitumen treatment extend from low plasticity sand/clays to gravels and crushed rock. It should be noted that the presence of some filler sizes is essential to the process and that poorly graded sands devoid of natural filler sized particles, do not respond well to treatment, as illustrated later in this paper when discussing stabilization of dune sands at

Table 2. Representative Data for Foam Treated Materials

Soil Group (Unified-Soil) Classification	Suitability For Use With Foam	Range of Bitumen Contents		Cohesion	Gravel Equivalency of Mix	Remarks
		Full Range	Optimum Range (Best Mix)			
GW	Good	1.5 — 5.0	2.0 — 2.5	300 — 700	1.25 — 1.5	Permeable Mixtures
GW-GC GW-GM	Good	1.5 — 5.5	2.0 — 4.5	300 — 400	1.25 — 1.33	Permeable Mixtures
GP-GC	Good	1.5 — 4.0	2.5 — 3.0	300 — 400	1.25 — 1.33	Low Permeability
GC	Poor	4.0 — 6.0	4.0 — 6.0	300 — 400	1.25 — 1.33	Impermeable. Bitumen Content critical. Can be improved by adding small percentages lime.
SW	Fair	3.5 — 5.0	4.0 — 5.0	100	Nil	Needs addition of -200 mesh filler.
SW-SM	Good	1.0 — 6.0	2.5 — 4.0	100 — 400	1.00 — 1.33	
SP-SM	Poor	4.5 — 6.0+	3.0 — 4.5	100	Nil	Needs lower penetration bitumen and addition of -200 mesh filler.
SP	Fair	1.0 — 6.0	2.5 — 5.0	100 — 300	1.0 — 1.25	May need addition of -200 mesh filler.
SM	Good	1.5 — 6.0	2.5 — 4.5	100 — 400	1.00 — 1.33	
SM-SC	Good	2.5 — 6.0	4.0	400 — 700	1.33 — 1.5	
SC	Alone — Poor (With lime — Good)	3.5 — 6.0+ —	4.0 — 6.0 3.0 — 4.0	400 — 700	1.33 — 1.5) 1.33 — 1.5)	Needs addition of small percentage of lime.

Brown's Road (see Table 8, and Figure 2). High Plasticity clayey gravels or sands also respond poorly to this process unless modified before the addition of foamed bitumen. Addition of filler in the case of deficient sands, and of lime with clayey materials, has been found to be advantageous. Layer equivalency data in Table 2 have been computed from Cohesion values using the method described by Zube (11) where the equivalent thickness of different cover materials is proportional to the reciprocal of the fifth root of their measured Cohesions. For the purpose of comparison of Cohesion value of 100 is assumed for untreated granular material.

Foamed bitumen mixtures in appropriate thicknesses may be used to advantage as replacement for conventional asphalt base courses in full depth asphalt construction or as alternatives to granular base

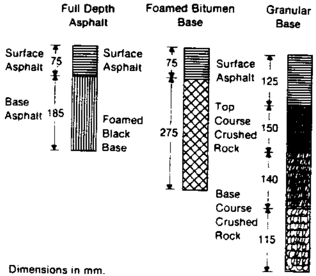

Fig. 1. Equivalent Performance Pavements.

coefficient in the range of 1.5 to 1.6 for the 4 percent foam treated Sydney breccia.

Figure 1 illustrates an example of equivalent performance pavement sections using alternative base course materials. The pavements are designed according to the Australian Asphalt Pavement Association's "Interim Guide for Structural Design of Asphalt Pavements" and details of calculations for the example shown are listed in Table 5. A relative thickness coefficient of 1.5 was used to determine the equivalent thickness of the foam treated base which may be compared to a figure of 2.6 for the granular base in this example. Table 6 lists typical cost comparisons using design data from Table 5 and representative costs for materials in S.E. Australia.

Foam mixes, particularly with crushed rock, are characterized by concentration of the bitumen within the "fines" and a tendency to leave the larger particles relatively uncoated. This feature results in good workability of the mix and is responsible for its unique properties particularly in comparison with treatments that deposit thinner bitumen films over the whole of the particle size range. One disadvantage of the types of mixture used to date is a relative lack of abrasion resistance at the surface and perhaps for this reason the use of foamed bitumen mixtures as wearing courses has not been generally pursued in Australia. Larcombe and Newton (14) have reported on particular jobs involving its successful use as a surface course, and examination of similar work carried out in Canada and North America suggests that this effect can be eliminated by attention to aggregate grading and use of slightly higher bitumen contents.

Laboratory studies have shown that greater abrasion resistance of foamed mixtures may be achieved by a heating and drying cycle followed

Table 5. Equivalent Pavement Design Calculation—Example (A.A.P.A. Guide—Ref. (17))

Requirements:	Design of city street; 500 commercial vehicles per day; annual growth 4%/annum; 20 year design life.
Input data:	Subgrade CBR-5
	Subgrade Modulus (E) ex Table 1 = 7500 lbs/in.^{2} approx. 50 MPa
	Design Number (N) = 4×10^6

Design Thicknesses:

(1) Full Depth Asphalt.	Thickness from Chart 2 = 10.2 in. (260 mm)
(2) Granular Base.	Minimum dense asphalt = 5.0 in. (125 mm)
	Granular base (CBR 80) = 6.0 in. (150 mm)
	Granular base (CBR 40) = 5.5 in. (140 mm)
	Granular base (CBR 20) = 4.5 in. (115 mm)
Equivalent foamed bitumen base design:	
(3) Foamed bitumen base.	Wearing course asphalt = 3.0 in. (75 mm)
	4% foam treated crushed rock = 10.8 in. (275 mm)
	(Assumes Relative Thickness Coefficient of 1.5)

by not compaction. The use of surface active agents designed to modify aggregate surfaces before foam addition has also been found to improve distribution of the bitumen during drying and re-mixing with a consequent improvement in cohesion. Table 7 shows laboratory test results for four foam mixes and a hot-mix control using good quality crushed rock meeting conventional binder course requirements. Mix 1 shows results for the standard foam technique of cold mixing and compaction followed by a three day curing period; cohesion is relatively poor due to "fines" deficiency in the aggregate (3 percent passing No. 200 (0.074 mm) sieve) and bitumen has not coated aggregate particles above 6.4-mm (0.25-in.) diameter. Mix 2 shows the improvement in cohesion obtained by a heating cycle and hot compaction; the drop in stability may be attributed to re-distribution of the bitumen over a wider range of

Table 6. Cost Comparison Calculations

Item	Typical Cost $ per m³ (solid)	Calculated Costs per m² Full Depth Asphalt mm	Full Depth Asphalt $/m²	4% Foamed Black Base mm	4% Foamed Black Base $/m²	Granular Base mm	Granular Base $/m²
Excavate and dispose	3.50	260	0.91	350	1.22	530	1.86
Surface course asphalt	50.00	75	3.75	75	3.75	125	6.25
Prime	—	—	—	—	—	—	0.12
Base course asphalt	43.00	185	7.96	—	—	—	—
4% Foamed Black Base	26.00	—	—	275	7.15	—	—
Top Course F.C.R.	14.00	—	—	—	—	150	2.10
Base Course F.C.R.	12.00	—	—	—	—	255	3.06
COMPARATIVE DEPTHS	mm	260		350		530	
COMPARATIVE COSTS	$/m²		12.62		12.12		13.39

Table 3. Range of Properties of Untreated Crushed Rocks Used in Table 4 Mixes

Material	B.S.	mm.	Melbourne Basalts	Sydney Breccias	Adelaide Quartzites
Grading	3/4"	19.1	90 – 100	95 – 100	90 – 100
(% passing)	1/2"	13.2	70 – 90	75 – 87	65 – 90
	3/8"	9.5	63 – 84	65 – 77	55 – 80
	3/16"	4.76	45 – 70	45 – 57	40 – 65
	No. 7	2.41	30 – 50	35 – 45	25 – 50
	No. 36	0.425	10 – 25	18 – 25	10 – 25
	No. 200	0.076	5 – 15	7 – 12	2 – 10
Liquid Limit			Up to 25	Up to 20	Up to 25
Plasticity Index			2 to 10	NP to 6	2 to 10

courses. Typically a "B" grade crushed rock is used with foamed 90-pen. bitumen at a level of 4 percent by weight. The classification properties of three commonly available types of crushed rock are shown in Table 3 and typical laboratory test results for these materials in the untreated state and when treated with 4 percent foamed bitumen are shown in Table 4.

A bitumen content of 4 percent in these materials provides high and permanent Cohesion values before and after exposure to moisture vapor while still maintaining values of Relative Stability above 25 before, and 20 after such exposure. At this bitumen content permeability

Table 4. Typical Mix Properties

% R90 Bitumen Content		Melbourne Basalts		Sydney Breccias		Adelaide Quartzites	
		Nil	4%	Nil	4%	Nil	4%
Dry Density (lb/cu. ft.)		136 – 141	137 – 144	134 – 137	135 – 137	130 – 134	130 – 132
Resistance Value	Before Soak	86 – 95	94 – 95	92 – 95	94 – 96	87 – 94	88 – 95
	After Soak	Collapsed	91 – 95	Collapsed	87 – 94	Collapsed	96 – 92
Relative Stability	Before M.V.S.	22 – 80	33 – 48	55 – 64	25 – 45	57 – 80	24 – 40
	After M.V.S.	10 – 48	32 – 44	36 – 40	20 – 25	28 – 41	19 – 25
Cohesion	Before M.V.S.	* – 465	200 – 500	290 – 420	400 – 500	* – 372	180 – 330
	After M.V.S.	0 – 90	250 – 500	56 – 112	440 – 500	25 – 125	150 – 280
U.C.S. (psi)	Before Soak	* – 1000	450 – 780	672 – 820	400 – 800	* – 564	325 – 600
	After Soak	Collapsed	200 – 450	Collapsed	184 – 400	Collapsed	140 – 250
Permeability (ml/24 hrs.)		500+	5 – 50	500+	15 – 30	165 – 500+	5 – 30
Swell (in. x 10[illegible])		2 – 3	Nil	0 – 7	0 – 13	2 – 9	Nil
Marshall Stability (lb.)			2,937		3,910		2,687
Flow (ins. x 10[illegible])			11.8		21.9		14.5

* Collapsed in handling.

is reduced to below 50 mls/24 hr and satisfactory Marshall stabilities are obtained. Shackel (9) in repeated load testing demonstrated that with Sydney breccia there is a marked increase in the number of repetitions required to attain a total strain of 2 percent in the range 1.5 to 5 percent bitumen content. At the 4 percent binder level there is a hundredfold increase over that for untreated material.

It has been shown that moisture level in the finished pavement is of significance in relation to performance and that the moisture in laboratory specimens is usually reduced to below 50 percent of optimum prior to testing (5). Shackel (9) found that the Resilient Modulus is maximized at a saturation of about 60 percent for a mix comprising Sydney breccia plus 4 percent foamed bitumen. It is recommended practice when using foamed bitumen mixtures to allow the pavement layer to lose 25 to 50 percent of its compaction moisture by drying prior to covering with an impermeable surface. This practice is validated by static and dynamic laboratory test results. The typical moisture contents of laboratory specimens at various stages of testing in Table 4 were:

Mix and compact — 5 to 7 percent
After curing — 1 to 3 percent
After 4 day soak — 3 to 5 percent
After 3 day MVS — 2 to 4 percent

The efficient design of pavements required that the relative performance or "Relative Thickness Coefficients"[3] of different materials be known. The thickness coefficients may be determined by full scale field testing; theoretical calculation from elastic moduli and Poisson's ratio; or, from correlation of specific test properties with actual performance. Zube (11) has proposed that the Cohesion value may be used to obtain a measure of "Gravel Equivalency"[4] and application of this procedure to 4 percent foamed bitumen treated crushed rock mixtures shown in Table 4 indicates gravel equivalents of 1.15 to 1.4—i.e., 1.15 to 1.4 in. of untreated aggregate are equivalent to 1.0 in. of treated material. Using a figure of 2.0 for the gravel equivalency of conventional asphalt base course, a relative thickness coefficient of between 1.4 and 1.7 is obtained for the foamed mixture, i.e., 1.4 to 1.7 in. of foam treated material is equivalent to 1 in. of conventional asphalt base.

Shook (12) has recently reported on results of the San Diego satellite experiments where it was demonstrated that *"Class 2"* and *"Class 3"* aggregate, bound with bitumen added either in cutback or emulsion form, exhibited similar levels of performance with Relative Thickness Coefficients of 1.5 to 1.6. Untreated granular bases in these experiments showed coefficients of 2.5 to 3.5. Limited application of multi-layer elastic theory using a program developed by the Commonwealth Scientific Industrial and Research Organization (13) has indicated a

[3] Related to 25.4 mm (1 in.) of high quality conventional asphalt base.
[4] Relates to 25.4 mm (1 in.) of untreated granular base.

of aggregate particles. Mixes 3 and 4 represent similar experiments where the aggrégate was pretreated with an imidazoline surface active agent prior to foam addition. The cold Mix 3 shows generally poorer properties than Mix 1 due to thinner films of bitumen distributed over a wider particle size range. Mix 4 compacted at 230 F (110 C) after drying shows a significant improvement in cohesion and may be compared to the hot-mix control in general properties although it is apparent that a satisfactory density has not been achieved.

Table 7. Potential Surface Course Mixes—Foamed Bitumen

	Foam Mix 1	Foam Mix 2	Foam Mix 3	Foam Mix 4	Hot Mix Control
90 Penetration Bitumen, % wt	5.0	5.8	5.0	5.0	5.8
Additive, % of aggregate wt	Nil	Nil	0.05	0.05	Nil
Compaction Temperature, F (C)	73 (23)	230 (110)	73 (23)	230 (110)	230 (110)
Compaction Moisture, %	6.0	0.5	6.0	0.4	Nil
Curing Period at 140 F (60 C), days	3	Nil	3	Nil	Nil
Moisture content after curing, %	0.7	--	0.4	--	—
Dry Density, lb/cu ft	136	147	140	146	151
Estimated Air Voids, %	10.6	7.5	9.3	9.5	4.5
Relative Stability	47	27	22	30	34
Relative Stability after M.V.S.	28	—	21	28	20
Cohesion	74	200	36	343	290
Cohesion after M.V.S.	161	—	209	328	340
Marshall Stability, lb	2150	2175	1450	2278	2870
Flow Value, in. $\times 10^{-2}$ (mm)	8 (2.0)	—	16 (4.1)	16 (4.1)	14 (3.6)

Aggregate Characteristics: High quality crushed rock suitable for conventional mixes

Grading:

Sieve No.	3/4 in.	3/8 in.	1/4 in.	7	14	25	36	52	100	200
(mm)	(19.1)	(9.5)	(6.4)	(2.41)	(1.41)	(0.71)	(0.425)	(0.280)	(0.149)	(0.074)
% Passing	99	79	59	49	34	24	19	12	6	3

EVALUATION AND PERFORMANCE OF FIELD PROJECTS

The foamed bitumen process is suited for use with materials ranging from low P.I. sand clays at one end to well graded crushed rock at the other. All need sufficient "fines" to produce the necessary mortar mix. Evaluation and performance details follow for two road projects constructed, each of which used a material representative of the extreme end of the above cited suitable materials range.

Dune Sands—Brown's Road, Shire of Flinders

Figure 2 shows the grading envelope for sands (nonplastic) which have produced satisfactory base courses after incorporation of foamed bitumen. The clean dune sand, and the overlying silty sand used in this project are also shown.

General

Brown's Road is a Tourist Road serving a popular ocean surf beach on the Mornington peninsula about 60 miles (96 km) from

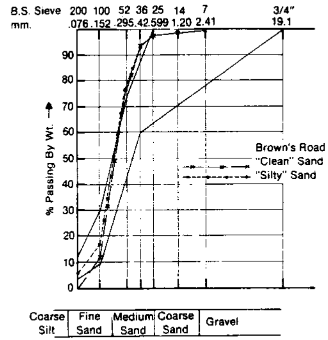

Fig. 2. Sand Gradings.

Melbourne. It traverses an area of deep sand dune overlain by some 15 cm (6 in.) of the same sand contaminated with silt. Unpaved roads corrugate rapidly and erosion by both wind and rainfall run-off is rapid. Standard pavements in the area consist of a bitumen seal on a 20 cm (8 in.) crushed rock base. Quarrying is resisted in this scenic area, and the dune sand was used with foamed bitumen both as an environmentally acceptable and attractive economic alternative to crushed rock base.

Mix Design

Properties of the sands and the trail mixtures are shown in Table 8. Increasing the proportion of clean sand in the blend clearly decreased the Relative Stability of the mix. Decreasing the bitumen content in the cleaner blend resulted in poorer mix quality, easier entry by water and a reduced Unconfined Compressive Strength after soak. Decreasing the proportion of clean sand and increasing the bitumen content produced more easily compacted mixes.

A maximum proportion of 60 percent clean sand was specified in the blend, and a bitumen content of 5 percent was chosen to give minimum acceptable Relative Stability and maximum acceptable "permeability." The bitumen used was a 60 pen. product, meeting the requirements of Australian Standard AS 10—1967.

Table 8. Physical Properties of "Brown's Road"—Sands and Mixes

Properties Before Treatment

Sieve Size (mm)	Clean Sand	Silty Sand	Blend with 25% Clean Sand % Passing	Blend with 60% Clean Sand % Passing
No. 7 (2.41)	100.0	99.5	99.6	99.8
No. 14 (1.41)	99.6	99.0	99.2	99.4
No. 25 (0.71)	98.8	97.9	98.1	98.5
No. 36 (0.425)	94.0	93.3	93.5	93.7
No. 52 (0.280)	74.5	75.7	75.4	75.6
No. 100 (0.144)	11.2	16.6	15.5	13.4
No. 200 (0.074)	0.8	5.7	4.5	2.7
Plasticity Index			← All Non-Plastic	→
*Optimum Moisture Content (%)			11.5	10.0
*Maximum Dry Density, lb/cu ft			110.5	109.8

Properties After Adding Bitumen

	Blend with 25% Clean Sand			Blend with 60% Clean Sand		
Bitumen Content (%)	4	5	6	4	5	6
*O.M.C. (%)		10.0			9.5	
*M.D.D., lb/cu ft		114.3			113.7	
Dry Density at Compaction, lb/cu ft	113.7	114.0	114.5	112.8	113.4	113.4
Resistance Value:						
Before Soak	94.5	94.5	94.5	94.5	95.0	94.5
After Soak	95.5	95.5	95.5	89.0	95.0	94.0
Relative Stability:						
Before M.V.S.	30	27.5	23	22	19.5	17.5
After M.V.S.	29	27.0	24	21	19.5	17.5
Cohesiometer Value:						
Before M.V.S.	241	180	246	244	249	220
After M.V.S.	316	270	345	392	429	405
U.C.S. (psi):						
Before Soak	326	316	316	258	274	252
After Soak	344	340	312	196	300	298
Permeability (ml/24 hr)	25	20	20	375	25	20

*Compaction by Hveem Kneading Compactor with foot pressure 350 psi.

Construction

The work was carried out during the winter season to minimize plant movement and erosion problems. A single pass three rotor stabilizing machine (Figure 3) mixed the full 20 cm (8 in.) depth as one layer. Initial compaction was by a seven tire pneumatic roller capable of varying tire pressures up to 689 kPa (100 psi) and total weight to a maximum of 28 ton. Final rolling was by a 9 ton, 11 wheel multi-tire, pneumatic roller.

Rain fell almost nightly during the work (Table 9) preventing the sand from drying either before or after the incorporation of bitumen. Mixing was carried out at Optimum Moisture Content (O.M.C.) (for compaction of the mix) to 2 percent above optimum. In spite of these conditions typical early gain in strength was recorded; field CBR values by Dynamic Cone were from 8 to 11 immediately after completion of compaction to a range of 17 to 27 after being open to light traffic and weather for a period of 1 to 2 weeks. During this period the moisture content remained essentially constant at O.M.C. to O.M.C. + 2 percent,

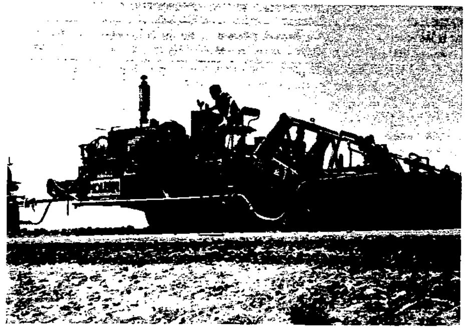

Fig. 3. Single Pass Stabilizing Machine Used on Brown's Road Project.

with the top 5 cm (2 in.) fluctuating as high as O.M.C. + 4 percent in some isolated areas after rain. This behavior agrees with laboratory test results which after several days exposure to moisture also showed a general strength increase.

Mixing and compaction were carried out between 19th June and 11th July, 1973. One localized area with extremely high clean sand content, could not be adequately compacted, as it sheared within the top 2.5 to 5.1 cm (1 to 2 in.) under the grader and roller wheels. Field testing showed the material remained at the CBR 6 to 8 level. This was corrected on 8th August by remixing with 25 percent crushed rubble and an additional 2 percent binder. The effect of this additional material can be seen in Table 10 which includes field measurements taken after 2 years service. Although the crushed rubble was used primarily to improve the stability of the mixture in its uncured or freshly mixed state, such improvement is also retained in the cured

Table 9. Brown's Road Construction

Date	C.B.R. Values	Dry Densities	Moisture Contents	Rainfall
11th July	8-11 (3 Sites)	94-97%	9-13%	[3.61 ins. on 16 days in 34 day curing period.*]
17th July	13 (Single Check)	---	9-12%	
20th July	--	---	10-16%	
24th July	12-19 (12 Sites)	---	10-14%	
2nd Aug.	17-27 (10 Sites)	94-97%	9-12%	
14th Aug.	Road Primer Sealed.			

*Maximum single fall of 0.94 in. (23.9 mm) on 6th August.

Table 10. Field Measurements—Brown's Road

Chainage and Depths			At Time of Sealing C.B.R.	At Time of Sealing M.C.	After 2 Years Service C.B.R.	After 2 Years Service M.C.
300	*L.H.S.	0-2"	18	11.3	68	
		2-4"	18	11.3	52	
		4-8"	18	11.3	53	
800	L.H.S.	0-2"	27	10.9	56	
		2-4"	27	11.9	54	
		4-8"	27	11.3	45	
1600	L.H.S.	0-2"	13	9.7	52	
		2-4"	13	11.5	74	
		4-8"	13	10.5	50	
2250	L.H.S.	0-2"	17	10.5	59	6.8
		2-4"	17	9.9	56	6.3 E
		4-8"	17	9.0	50	6.4
3350	L.H.S.	0-2"	17	11.5	53	4.9
		2-4"	17	13.0	57	4.6 C
		4-8"	17	13.6	50	4.0
3658	R.H.S.	0-2"		10.9	94	
		2-4"	Re-mix		94	
		4-8"	August 8	8.7	94	

* Left hand side of roadway in direction of increasing chainage.
E—Embankment site near 2250 ft (686 m) 1 in. = 25.4 mm.
C—Cutting site near 3350 ft (1021 m)

state. Hence the marked increase in CBR values from 6 to 8 to 94 over the two year period includes a significant component due to the improvement in grading and particle angularity gained from addition of the crushed material, and is not due solely to the increased bitumen content.

Performance

The moisture content has dropped over the 2 years, and is now of the order of 30 to 60 percent of that existing when the bituminous seal treatment was applied. In the same two years of service the CBR value has generally trebled in the typical sand mix. The moisture content is now lower at the base of the pavement layer than at the surface suggesting that drying out has been by drainage through the underlying clean uniform sand subgrade. These trends in CBR value, and moisture content, with time in service are confirmed by measurements on other roads in the area constructed at the same time.

In spite of the low CBR values recorded at the time of sealing the road there is no cracking or rutting visible after 2-years of service with light traffic and extended periods of high pavement temperature. Winter traffic volumes vary from 210-230 vehicles per day at weekends to 150-210 vehicles per day, including an estimated 15 percent truck traffic from an adjacent sand pit, during the week. Surface temperatures for this road are typically those reported for the Melbourne area by Dickinson (15) and frequently exceed 60 C (140 F).

Non-destructive testing was carried out by the Australian Road Research Board using the Rayleigh wave technique (16). Tests were

made on Brown's Road and an adjacent road constructed in an identical manner at the same time. The results indicated no appreciable change in dynamic Young's Modulus immediately after mixing and compaction had been completed. However, three weeks after mixing and compaction, an increase of 50 percent was recorded, and after 4 months the dynamic Young's Modulus was three times that of the original untreated material.

Crushed Rock Mixtures—Springvale Road

General

This project was constructed to provide in-service data on the structural performance of foamed bitumen mixtures. A crushed basalt considered too poor in quality for use, in the untreated state, in the upper 15 cm (6 in.) of pavements was selected. Four percent of foamed bitumen (90 pen.) was used to improve the characteristics of this material to a high performance level.

Although too early to comment on in-service performance as such, the background data to this project are given to illustrate the basis for selection of (a) a low cost rock likely to perform well with foamed bitumen, and (b) a method by which layer equivalency values can be assigned to various paving materials.

Pressure cells of the strain gauged diaphragm type, strain gauges of both wire resistance and Bison Coil type, plus thermocouples and LVDT's have been installed for data measurement during service. They are oriented to measure vertical, radial and tangential stresses and strains for comparison with those calculated using laboratory measured values of Resilient Modulus in the C.S.I.R.O. pavement response or evaluation program, called "Cranlay." (13)

Mix Design

Tables 11 and 12 and Figures 4 and 5 show the properties of the crushed rock used, the properties of the 4 percent foamed bitumen treated mixtures selected for use and the plots of the effect of changing bitumen content on this material. The properties of similar mixes made from different types of rock, including one (the Sydney Breccia) for which repeated load response was known in this type of mixture, are given in Table 4.

The data indicated between 3 and 4 percent bitumen to be the optimum range from the static test viewpoint. It also showed the proposed basalt mix to be at least comparable and probably superior to the breccia mix used for dynamic testing under repeated loading. Repeated loading test data (9) indicated that for the breccia mix a bitumen content of 4 to 5 percent was needed to give the best response when compacted and in service at saturations of 50 to 70 percent. This degree of saturation is readily and usually obtained in practice, hence for purely dynamic loading reasons a foamed bitumen content in the 4 to 5 percent area is preferred.

Table 11. Classification Test Results on Untreated Material

Secondary Mineral Content	28% (point counting method on thin section)
Sand Equivalent (45 secs.)	45
Extended Sand Equivalent (E)	11
Washington Degradation	31
Liquid Limit	19.3
Plasticity Index	2.4

Particle Size Distribution:

Sieve Size (mm)	% Passing Dry	% Passing Wet
3/4 in. (19.1)	100.0	100.0
3/8 in. (9.5)	72.2	68.3
3/16 in. (4.76)	47.3	46.6
No. 7 (2.41)	34.7	32.8
No. 14 (1.41)	25.8	23.3
No. 36 (0.425)	18.5	16.4
No. 100 (0.149)	13.0	12.8
No. 200 (0.074)	8.6	10.0

On the basis of these figures the marginal basalt was selected for use as having good properties when mixed with foamed bitumen plus maximum cost benefit potential. A 4-percent bitumen content was chosen as a practical compromise to obtain near optimum results for both static and repeated load tests.

Construction

The foamed bitumen black base material for this work was mixed in a stationary continuous twin-shafted pugmill with square paddle tips, at a rate of 150 ton per hour. Three cold feed bins were used to control the grading, and bitumen for foaming was supplied by a calibrated variable speed positive displacement pump. Water for foaming was controlled at 1.7 percent of the bitumen flow rate by an automatic flow rate controller with variable setting. The mix, being cold and at the optimum moisture content for compaction, could be either paver or grader spread. Standard rolling techniques as for crushed rock base course materials were used, with the exception that minimal amounts of water were necessary to prevent roller pick-up or surface dusting.

Table 12. Physical Properties with and without Incorporation of 4% Foamed Bitumen

Test		Untreated	Treated (4%)
Resistance Value	Before Soak	95	94
	After Soak	Collapsed	93
Relative Stability	Before M.V.S.	70	33
	After M.V.S.	15	53
Cohesiometer Value	Before M.V.S.	465	499
	After M.V.S.	Collapsed	499
Unconfined Compressive Strength	Before Soak—(psi)	992	780
	After Soak—(psi)	Collapsed	260
Permeability (ml/24 hrs.)		500+	10
Swell, (in. × 10^{-3}) (mm)		3 (.08)	Nil

Performance

Deflections and stresses in the pavement, assuming an applied uniform vertical pressure of 550 kPa (80 psi) applied over a circular area of radius 15.24 cm (6 in.) and calculated using C.S.I.R.O. computer program "Cranlay" for layered elastic systems, are listed in Table 13. The elastic constants used in the computations were obtained by repeated loading of Triaxial specimens using the Volcanic Breccia examined by Shackel (9). In his work the rate of loading was 30 cycles per minute equivalent to a load moving slowly at approximately 0.5 km per hour. "Free" end plates were used, and the deviator stress used was high at 165 kPa (24 psi).

The figures used for the elastic constants in Table 13 are thus considered realistic for the untreated granular material and the foamed bitumen treated mixtures, but may be somewhat pessimistic for the hot mixed asphalt layer because of creep effects due to this slow rate of loading. However, a large change in M_R value for this 3.18 cm (1.25 in.) thin hot mixed asphalt layer has little effect on the

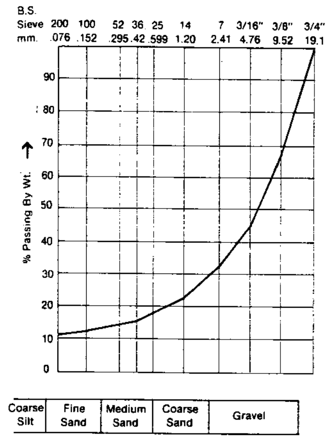

Fig. 4. Crushed Rock Grading Springvale Road.

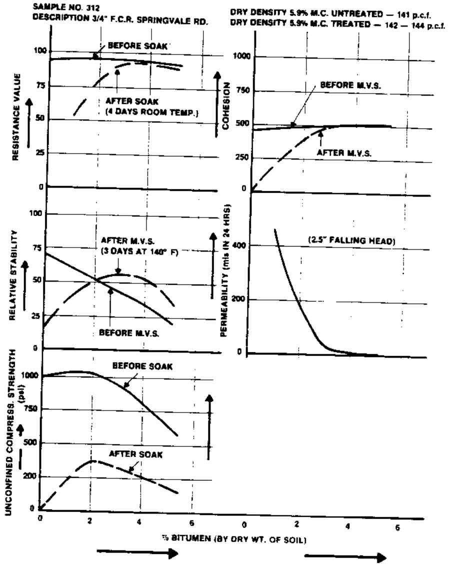

Fig. 5. Mix Properties.

computed stresses and strains. The subgrade layer was assigned a value of 51.6 MPa (7,500 psi) for its Resilient Modulus based on its CBR value of 5 and the AAPA design guide (17). No attempt was made to include the effect of braking and acceleration stresses, and it is because of this that the two alternate surface treatments were adopted—single seal and 3.18 cm (1.25 in.) of hot mixed asphalt.

The figures in Table 13 indicate comparable deflections and stresses in the subgrade for all three cases. The higher tensile stresses shown for the 4 percent foamed bitumen layers are considered allowable due to the high "Cohesion" of this material. With the

Table 13. Computed Deflections and Stresses

Pavement	Layer No. Material and Depth	Subgrade Max. Displacement (in.)	Surface Max. Deflection (in.)	Max. Stresses (psi) Comp.	Tens.
Standard Granular Design	Single Seal		0.097		
	1. 4" of 3/4" Wet mixed crushed rock.			80.0	3.8
	2. 4" of 2" Ripped Sandstone (0-6 P.I.)			67.6	Nil
	3. 5-3/4" of Ripped Sandstone (0-12 P.I.)			39.4	1.7
	4. Subgrade C.B.R. 5-6	0.038		17.5	2.4
Alternate No. 1 11" of 4% Foamed Black Base.	Single Seal		0.057		
	1. 11" of 4% Foamed Black Base			80.0	18.9
	2. Subgrade C.B.R. 5-6	0.038		17.7	2.3
Alternate No. 2 Asphalt on Foamed Black Base.	1. 1-1/4" of 1/2" max. agg. size asphalt.		0.060	80.0	3.2
	2. 9" of 4% Foamed Black Base			78.5	20.6
	3. Subgrade C.B.R. 5-6	0.039		19.0	2.5

Unconfined Compressive Strength in practice being somewhere between 1790 kPa (260 psi) and 5400 kPa (780 psi) dependent on moisture content, the tensile strength is estimated at about 207 to 550 kPa (30 to 80 psi) with the former figure representing the unlikely case of "soaked" material.

Thus in alternate 1 we have an indicated equivalent thickness of 27.94 cm (11 in.) of the foamed bitumen mixture to 34.93 cm (13.75 in.) Granular, or 2.54 cm (1 in.) Foamed Black Base to 3.18 cm (1.25 in.) Granular. In alternative 2, considering the "thin" hot mixed asphalt layer to have the same equivalency as the foamed bitumen base course material, we have 2.54 cm (1 in.) Foamed Black Base equivalent to 3.40 cm (1.34 in.) Granular.

The above information although based on limited data provided a reasonable basis for the adoption of 27.94 cm (11 in.) and 22.86 cm (9 in.) as the base course thicknesses in which to install the stress and strain measuring equipment. Assuming a "Relative Thickness Coefficient" (inches of specified base material per 1 in. Asphalt) of 2.0 for general granular bases, we then have relative thickness coefficients for the two 4 percent Foamed Black Bases of 1.60 and 1.49 respectively. Closer estimation must await the collection of specific data from this project. All indications to date suggest these assumptions to be valid.

CONCLUSIONS

From the work conducted to date it is concluded that:

a. The foamed bitumen process has proved an economically viable means of stabilizing and upgrading marginal pavement materials in Australia. The process may be used to incorporate relatively low amounts of bitumen into many soils to provide clean, easily handled mixtures which may be readily compacted and possess significant improvements in structural properties over the untreated materials.

b. At bitumen levels of 4 percent and above the foam process may be effectively used with crushed materials to provide "black bases" as attractive alternatives to either granular materials or conventional hot mix asphalt. Current indications are that 1.5 inches of foamed black base is equivalent to 1.0 inch of conventional hot mix asphalt.

c. Processing costs associated with manufacture of bitumen emulsions or cutbacks are eliminated by the use of foamed bitumen as is the need for transport and subsequent removal of water or solvent from the mix prior to compaction.

d. Foamed bitumen allows the use of locally available materials in many cases and thus can offer significant cost savings. The process being dust and vapor free is also environmentally attractive.

ACKNOWLEDGMENT

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Discussion

MR. J. E. HUFFMAN (Prepared Discussion): The authors are to be complimented on an interesting paper as well as a timely one when considering the interest today in energy conservation. In the United States, cold-mix paving technology—mostly with emulsified asphalts—is rapidly advancing through increased laboratory research and field experimentation. It is encouraging to see cold-mix research being pursued in other parts of the world.

A few important questions did arise after reviewing an advanced draft of the paper. The first deals with the importance of consistently obtaining foamed bitumen of desired properties—this referred to in paragraph 5 and evident by the data in Table 1. The Mobil production method may indeed be an improved system, but what field tests are used to check the foamed bitumen properties? Also, the properties of the foamed bitumen used in laboratory testing for mix and pavement thickness design must be similar to that which ultimately result on the project. This condition is one which periodically does not occur for emulsified asphalts with the differences in product between the laboratory and field leading to construction and pavement performance problems.

Relative to the laboratory testing procedures outlined in paragraph 8, the use of oven curing at 60 C (140 F) for specimens will be questioned by some for foamed bitumen as it presently is when using emulsified asphalts. This environment does not really simulate field curing conditions and with emulsions has not only produced accelerated dehydration but also improved asphalt coalescence beyond that obtainable under project conditions. It is suggested that both the early and ultimate strength of cold-mix paving materials is of importance with ambient curing being commonly selected for the former and this type of curing plus vacuum desiccation being used in a new mix design method to obtain ultimate values.

In paragraphs 13 and 14, reference is made to the concentration of the bitumen in the fine sand and silt fraction and also that this results in a stronger mortar fraction than does bitumen emulsion. In my experience, this concentration of the bitumen in the finer aggregate fractions is not uncommon when using slow setting (SS) emulsified asphalts with some engineers expressing much concern about the uncoated coarse particles [+ No. 4 (4.76 mm) sieve]. Relative to this inability of foamed bitumen to coat coarse aggregate, very popular in the United States recently has been the construction of logging roads using a cold plant-mixed coarse open-graded emulsified asphalt base (crushed aggregate, 100 percent passing 1-1/2 in. (38-mm) sieve, 0-5 percent passing No. 8 (2.38 mm) and 0-2 percent passing No. 200 (0.074 mm). It is possible to achieve good coarse particle coating using a medium setting (MS) emulsified asphalt but apparently this would not be possible with your present foamed product. The MS emulsions usually contain some solvent and the question arises as to the possibility of foaming a cutback asphalt such as a high viscosity medium curing grade (MC) for this type of application.

Discussed at some length is the thickness design of pavements incorporating foamed bitumen mixes with several comments about equivalencies and thickness coefficients. Modern pavement design methodology not only includes consideration of the strength (modulus) of treated layers but also their fatigue properties. I am most interested in this characteristic in the foamed bitumen mixes placed to date as indicated are relatively low asphalt contents. P. S. Pell and K. E. Cooper presented a most interesting paper at the 1975 AAPT Meeting in Phoenix on the effect of various mix variables on fatigue performance which included consideration of the very important asphalt binder content (volume).

The final item relates to climatic limitations for cold-mix paving with foamed bitumen. Not indicated is a minimum air temperature for mixing and/or spreading for this work. It is indicated that rain fell almost nightly during the Brown Road paving but apparently without causing major problems. Can this type of construction proceed during light rainfall provided the moisture content does not increase appreciably above that optimum for compaction?

Congratulations again on your paper and hopefully more information will be developed about the use of foamed bitumen in Australia.

DR. CHARLES A. PAGEN: As mentioned at the start of my presentation of the Foamed Bitumen technical paper, it is unfortunate that my research colleagues from Mobil Oil Australia, R. H. Bowering and C. L. Martin, are unable to be here today. However, the excellent questions raised by Mr. John Huffman and also any other questions raised during the discussion session will be forwarded to the authors for their comments in the final Authors' Closure.

I have a few comments on the key questions asked by John Huffman. Although some of the other questions raised are beyond the scope of the paper, I feel certain that the authors will be able to respond to them because of their many years of experience with foamed bitumen in Australia. As mentioned in the paper, foamed bitumen has been used in Australia since the late 1960's.

The first question was essentially, What field tests are used to check the foam properties? The second question was, Are the properties of the foamed asphalt mixes similar for lab and field produced foamed paving mixes? The lab and field foam producing systems are carefully calibrated. The half-life of the lab and field foamed bitumen is rigorously controlled. The foam half-life is defined as the time for the foam to deflate to one-half of its original volume. The expanded volume of the foam is also carefully controlled. The most effective foamed bitumen has an expanded volume of ten to 15 times the volume of the original hot bitumen. This expanded volume is produced by injecting about one to two percent water into the hot bitumen. In Australia they also check the physical properties of the recovered field asphalts and these are compared to the properties of the lab asphalts. Additional laboratory tests are also conducted to evaluate the strength and durability properties of the lab compacted foam paving mixes, and these properties are compared to the properties obtained from lab tests on undisturbed samples of field compacted foamed paving mixes.

The next question was, Can foamed bitumen be used to coat coarse aggregates? There is a table in the paper (Table 2) in which the Australians comment on the suitability of using foam bitumen with a wide range of soil types. In this table the soils are classified by the Unified soil classification system. The table specifically covers the suitability of using foam with selected materials, and the data are representative for foam treated soils in Australia. The table also shows the range of bitumen contents which should be used for the selected materials, the gravel layer thickness equivalency values of the mixes, typical cohesion values for the mixes and general remarks on the quality of the foamed materials. The cohesion values are evaluated in the Hveem cohesiometer test. The layer thickness equivalency values in Table 2 have been calculated from the cohesion values using a method described by Zube. Thus, at low asphalt contents the foam seems to coat the fine portions of the mix first, while at higher asphalt contents more of the various size fractions, including some of the coarse particles, are coated. It can be observed in the table that suitable materials for foamed bitumen treatment cover a wide range of soil types and gradations and extend from gravels and crushed rock to sand-clay materials.

The last question I am going to comment on is, Can foamed asphalt construction be used during light rainfall? During the construction of one of the test roads reviewed in the foamed bitumen paper, rain fell almost nightly and the construction of the road continued without any major problems. It seems that construction can take place during light rainfall provided that the water content of the soil does not increase appreciably above the optimum moisture content for compaction.

I have briefly commented on the key questions asked by John Huffman. All of these questions will be forwarded to Mobil Oil Australia for their response in the Authors' Closure.

MR. CHARLES R. FOSTER: Can you foam a silicone treated asphalt?

DR. PAGEN: Some work has been conducted in this area by Mobil Oil Australia. They are aware that very small quantities of silicone additives are sometimes used in bitumens as defoamants. I believe that the foaming conditions for these silicone treated bitumens may be modified to produce foamed bitumens with a satisfactory foam life.

AUTHORS' CLOSURE: We thank Mr. Huffman for his interesting discussion and the pertinent questions raised. Field tests used to check the foam quality are analagous to those used in the laboratory, i.e., collection of 2 liters of foamed bitumen; measurement of time to collapse to half its original volume and determination of the initial expansion. Occasionally differences are found between field mixtures and those prepared in the laboratory, but in general, correlation has been good.

The question of laboratory curing procedures is one which has been raised before and is obviously a most important aspect. We have conducted studies involving the curing of foamed bitumen treated mixtures over the range of temperatures from 23 C (73 F) to 60 C (140 F) and our findings indicated that temperatures in that range had little or no affect on measured properties. We recognize, however, that this may not always be the case and work is currently planned in which ambient curing and vacuum dessication methods are to be used in line with the new Asphalt Institute design procedure (PCD-1).

As emphasized in the paper, the foam process is especially suited to treatment of aggregates containing a fine sand or silt fraction at levels of 5 percent and above. The bitumen is concentrated in the finer fractions to build a strong mortar and as such the larger aggregate particles remain relatively uncoated. Therefore, we would not expect the foamed bitumen process to completely coat all the coarse aggregate particles in the open-graded base mix described by Mr. Huffman as being used on logging roads in the United States. However, we agree the use of solvents to improve such coating would be beneficial. In this regard our work has shown that bituminous based products with viscosities as low as 25 cps at the operating temperature may be satisfactorily foamed. Such products would include medium curing cutbacks MC-3000 and MC-800.

With respect to the comment on fatigue properties, some work on mixture characteristics has been conducted at the University of New South Wales in Australia. Most of this work has been completed and is reported on in Reference 9 in the paper. In this work the response to repeated loading was measured in terms of axial strain components and Resilient Moduli, but no direct attempt was made to assess fatigue life. We therefore are unable to offer any specific or positive comments on this aspect at this time.

However, we agree that fatigue properties of foamed bitumen mixtures are important and that the binder content is of special significance. Perhaps further study of results in Shackel's paper could give some measure of fatigue properties in comparison with asphalt. Fatigue has not proved a problem in our field work carried out over the last seven years.

The final question related to climatic limitations for satisfactory work with foamed bitumen. We have carried out work at air temperatures as low as 10 C (50 F) but it should be noted that the degree of dispersion of the bitumen and the quality of the mix obtained depends heavily on the temperature of the aggregate and its nature. We have found that most aggregates have a "critical" temperature of between 13 C (55 F) and 23 C (73 F) below which mixes of poor quality are obtained.

Use of a higher foaming temperature or lower viscosity binder assists work at low temperatures but is not a complete solution. Light rain during construction is not a problem providing adequate compaction can be achieved.

Mr. Foster's point on whether silicone treated asphalts can be foamed is well made. Some work has been done in this area. Generally, it has been found that small concentrations of silicones drastically reduce the expansion and stability of the foam to the point where it cannot be satisfactorily used. However, a number of surface active agents have been found that, at least partially, restore the original foaming characteristics.