Foamed Asphalt in Bituminous Paving Mixtures

LADIS H. CSANYI, Professor in Charge, Bituminous Research Laboratory
Engineering Experiment Station, Iowa State College

●THE physical properties and characteristics of the various bituminous binders used in bituminous paving mixtures greatly influence the manner in which such mixtures are made and the methods used in laying the mixes. Among the physical properties and characteristics, viscosity and surface tension of the binder are of particular importance. The viscosity of the binder is significant both in the manufacture and laying of the mixture. In making the mixture the binder must be liquid enough to flow readily through the entire aggregate mass and develop films of binder around the aggregate particles. In laying the mixture the binder must remain sufficiently plastic for easy and smooth spreading, and as soon as the mixture is spread it must harden rapidly so that the pavement may be compacted and opened to traffic as quickly as possible. The surface tension of the binder is especially significant in mixing. Adhesion between the film of binder and an aggregate particle depends largely upon the surface tensions of the two materials and the interfacial tension developed. The surface tension of the binder must therefore be such, in relation to that of the aggregate, that surface moisture on the aggregate can be displaced and a strong physical bond generated between the binder and aggregate. The importance of these two properties has been recognized; and processing, mixing and laying practices have been adjusted accordingly.

In the preparation of high type plant mix hot bituminous paving mixtures, with asphalt cement used as the binder, the viscosity of the binder is adjusted and controlled by the temperature of the binder and the aggregates. A relatively high temperature must be maintained in this type of mix during transportation and laying to assure a desired plasticity for spreading. Once spread, the binder hardens rapidly, permitting compaction and the opening of the pavement to traffic without undue delay. The heating of the binder to adjust its viscosity and heating of the aggregates to dry them and maintain the temperature of the mix are costly. Such mixes are therefore used generally for high type heavily travelled pavements.

On roads which do not need or cannot afford such high type mixes, other binders, such as cut-back asphalts or emulsified asphalts, can be used as the binder. Since the viscosity of a cut-back asphalt is adjusted by the type and quantity of solvent added to the base asphalt cement, the need for further adjustment of viscosity of the binder by heat during mixing is materially reduced. When this binder is used in conjunction with wetting agents, the heating of the aggregates can also be materially reduced. The viscosity of an emulsified asphalt is adjusted by the method used in preparing the emulsion, by the type of emulsifier used, and by the quantity of water added. A wide variety of grades of emulsified asphalts are available to meet various applications. When an emulsified asphalt is used in a bituminous mix as the binder, the need for heating the binder is practically eliminated. Furthermore, by virtue of the emulsifying agent used in this type of binder, good adhesion, even with cold and damp aggregates, can be attained. When emulsified asphalts are used in a mixture, heating of either or both the binder and aggregate can be materially reduced. Satisfactory mixes have been produced with the use of either cut-back asphalts or emulsified asphalts.

Although production of a bituminous mix is simplified when these materials are used as the binder, laying procedures become more complicated. Since the binder should set rapidly after the spreading of the mix to permit proper compaction, the solvent in a cut-back asphalt should be removed rapidly, the emulsified asphalt should break at the proper time, and the water released from the emulsion should be eliminated quickly. For these reasons mixes using these materials as the binder must be aerated to permit the evaporation of either the solvent or the water. This not only requires additional construction equipment and operations, but it also delays the opening of the road to traffic. So, although the use of these materials as binders improves one phase of the procedure, it falls short in another.

An ideal binder for use in low cost paving mixtures then would be one whose physical properties, such as viscosity and surface tension, were such that cold and even damp

aggregates could be used in mixing, retaining a desired plasticity of the mix until spread and, after spreading, the mix would set quickly.

Since this discussion deals with asphalt cements, the question arises as to how the physical properties of a bituminous binder may be adjusted in other ways without altering its chemical composition so that it may approach more nearly the properties and characteristics desired in an ideal binder.

One way in which this could be accomplished is by foaming the binder. Anyone who has had the misfortune to encounter a large mass of foamed asphalt has had an unwelcome opportunity to become acquainted with some of its unusual properties at first hand. A relatively hard asphalt cement, when foamed, expands greatly in volume. The foam creeps and flows even at low temperatures, penetrating dirt, clothing, shoe leather, or anything it comes in contact with, and oozes into cracks and crevices. The foam remains soft even at temperatures at which the parent asphalt cement has stiffened materially. The foam has a rubbery nature and is extremely sticky, adhering tenaciously to all types of materials it touches, and once it has stuck it is very difficult to remove or clean up. Uncontrolled foaming of asphalt around a plant is a considerable nuisance and should be guarded against and avoided. Chemicals are now available to prevent foaming or check it, should it get started, and thus avoid the mess it creates.

Although uncontrolled foaming of asphalt is highly undesirable, when the usual properties of the foam are considered, a foam under proper control could be advantageously used in preparing bituminous mixes.

A study of foamed asphalt discloses many interesting features, which when applied to bituminous mixes, could be used to advantage. Asphalt cement and other bituminous binders expand to many times their original volume when foamed. Therefore, if a quantity of asphaltic binder is applied as a foam, a wider and more uniform distribution of the binder can be obtained in mixing with aggregates than if the same quantity of binder is used as a liquid. An asphalt cement having a penetration of 85 to 100, when foamed, will have a penetration of over 300 at the same temperature for some time after it has been foamed. Chemical constituent tests indicate that the asphalt has not changed even though its consistency and viscosity have changed. This change in physical properties is due no doubt to the bubbles of gas or vapor the mass of material contains. Therefore, if foamed asphalt is added in mixing, the distribution of the binder throughout the aggregate can be accomplished at a much lower temperature than if the binder is added as a liquid. Further, since the binder remains soft for some time as a foam, mixes using foamed asphalt as the binder can be laid at lower temperatures. The foamed asphalt cement has a rubbery nature and is extremely sticky, with both high cohesive and high adhesive properties. When a foamed asphalt is used as a binder in a bituminous mix, it would be expected that there is improved adhesion between binder and aggregate, and a more cohesive mix would result. Preliminary tests indicate that this is true. The high adhesive property noted is no doubt due to the high wetting power generally exhibited by foams. The modified surface tension of the asphalt as a foam probably plays an important part in this behavior. Another great advantage is that the asphalt cement is in the form of bubbles. Here we have ready-made thin films of asphalt cement with powerful natural surface tension forces available to coat particles of matter on contact as the bubble breaks. The fact that foamed asphalt will penetrate small voids and crevices can be utilized to advantage because foamed binder will penetrate agglomerations of dusts which liquid asphalts will only coat with a layer of binder. Foamed asphalt thus lends itself more readily to soil stabilization than some other binders.

The various desirable properties of foamed asphalt can be utilized practically and their advantages gained in preparing bituminous mixes only if the foamed binder is under close control. The asphaltic binder must be foamed at the proper time, at the desired place, in the required quantities, and in a prescribed manner. The condition of the foam, the size of the bubbles, and other factors must also be controlled to obtain consistant results.

Foamed asphalt can be created easily by several methods. One involves the addition of small quantities of water to the asphalt and then heating the asphalt. The same result

is secured by gradually injecting small quantities of saturated steam into the heated asphaltic binder. The problem that had to be solved in this development was the generation of a foamed asphalt in the quantity and kind desired, at the place, time, and in the manner in which its properties could be most effectively utilized.

This problem was solved by the development of a nozzle for foaming a bituminous material instantaneously into a foam of a desired character and for introducing a desired quantity into a mixer at the proper time and in the proper manner. The nozzle devised consists of a body, nozzle tip, steam tube, and its adjustments and other appurtenances (Figure 1). The asphaltic binder enters the nozzle through the body and passes on to the nozzle tip. The saturated steam enters the nozzle by way of the steam tube which carries it to the tip of the nozzle. The steam leaving the tube combines with the bituminous binder just above and in the throat of the nozzle tip orifice, creating the foamed asphalt. The foamed asphalt is then emitted from the nozzle by the flow of the steam and binder through the nozzle. The type of foam produced can be controlled by the dimensional characteristics of the throat of the nozzle orifice and the position of the end of the steam tube in relation to the entrance to the throat; an adjustment is provided to set this position, and to control the quantity and pressure of both the steam and binder introduced into the nozzle.

Two basic types of foam can be produced by this nozzle. One type of foam created is referred to in this paper as a "discrete foam." This foam is in the form of sepa-

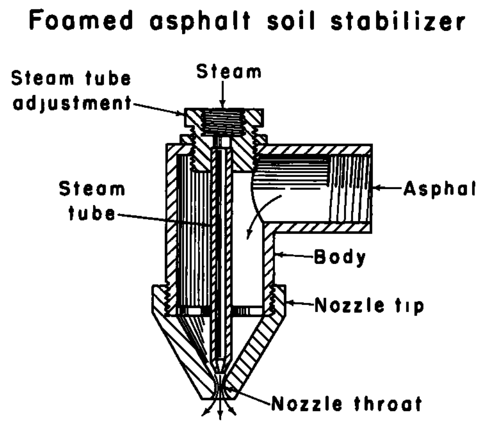

Figure 1. Foamed asphalt nozzle.

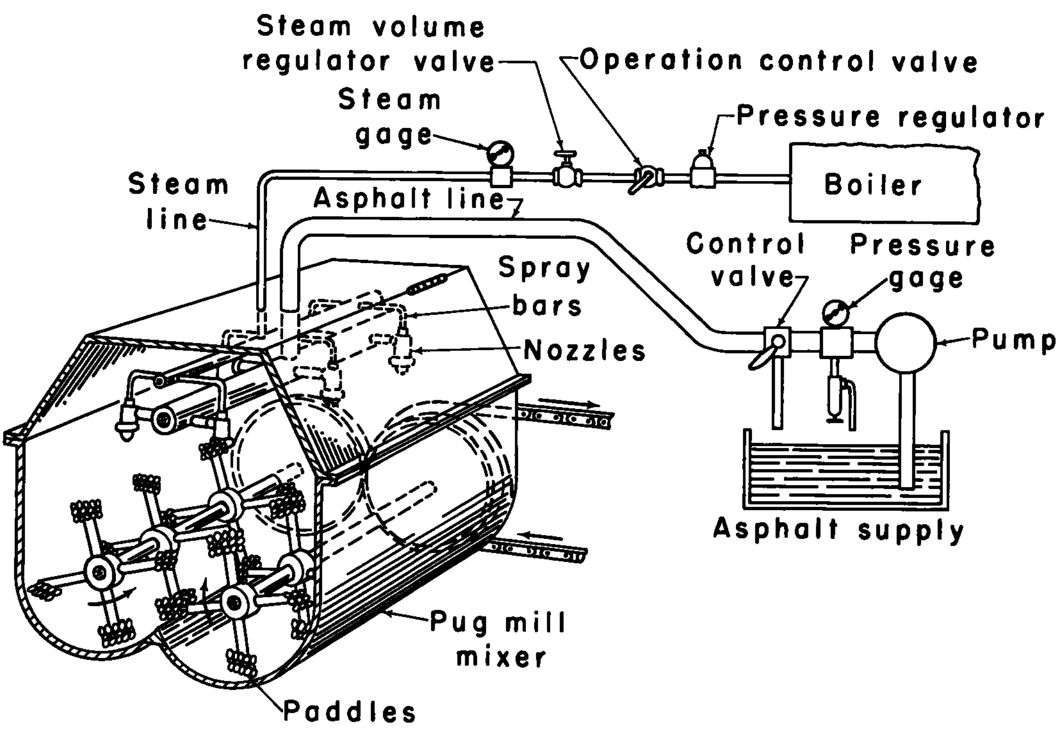

Figure 2. Foamed asphalt system.

rate individual small bubbles as it leaves the nozzle. The size of the bubbles can be controlled by a steam tube adjustment and by the adjustment of the steam and binder pressures when the discrete foam nozzle tip is used. A nozzle equipped with a discrete foam tip, under proper adjustment, will create a discrete foam with a small quantity of steam at 60 to 90 psi and binder pumped at 50 to 80 psi. The binder pressure must always be below that of the steam pressure to prevent binder backing into the steam tube. Bubbles of various sizes can be produced within these ranges of pressures by other nozzle adjustments.

The other type of foamed binder which can be created by this nozzle is referred to as a "concentrated foam" in this paper. In this case the bubbles of the foamed binder are joined together and a mass of foam is emitted from the nozzle. This type of foam can be produced by a concentrated foam nozzle tip and nozzle adjustment with saturated steam pressures as low as 35 psig and binder pump pressures as low as 20 psig. A wide range of foam characteristics can also be attained in this case by adjustment of steam and binder pressures and quantities admitted to the nozzle, and adjustment of the setting of the steam tube. It should be noted that in the operation of the foaming nozzle the steam primarily is used to create the foamed binder, and secondarily, by varying the pressure and quantity of the steam, it is used to control the character of the foam in some measure. The steam also serves to heat the nozzle and blow the nozzle orifice clear of foamed or congealed binder; the nozzle is thus in good working order even under intermittent operations.

After a means of generating a foam of a desired character was devised, a method of applying the foam in a mixer in the required quantity, at the proper time and in a suitable manner was necessary. A spray bar system as shown in Figure 2 was devised. The spray bar is fitted with the number of nozzles needed to distribute the foam in the mixes uniformly. The asphaltic binder may be measured either in a weigh tank or by a meter and then pumped through the asphalt line and the spray bar to the nozzle. The asphalt system is fitted with such appurtenances as a control shut off value pressure gauge, return circulating line, and pressure relief valve. Since the asphaltic binder need never be pumped in excess of 80 psi, standard low pressure piping may be used in this system. The steam needed for the foaming of the binder can be generated in a steam boiler having a pressure range of 45 to 100 pounds. In the steam line from boiler to nozzle, or from a local source of steam to the nozzle, must be a pressure regulating valve, a shut-off valve, a volume control valve and a steam pressure gauge. The pressure regulating valve is used to adjust the pressure of the steam being supplied to the nozzle. A volume control valve, which may be a simple needle valve, controls the quantity of steam furnished to the nozzle. Adjustments can readily be made to produce the foam characteristics desired with these control devices in the system.

The operation of the foamed asphalt system is simple once the proper nozzle adjustments and control settings have been made. The steam is turned on first to clear the nozzle tips, to remove moisture condensed in the steam line and to prevent the binder backing up in the steam tube of the nozzle. The binder is then pumped to the nozzle where the steam foams the binder and foamed binder is emitted from the nozzle into the mixer. When the proper quantity of binder has been introduced into the system, it is shut off. After the binder is shut off the steam flow is continued to clear the nozzle of binder. Then the steam is shut off until the next sequence.

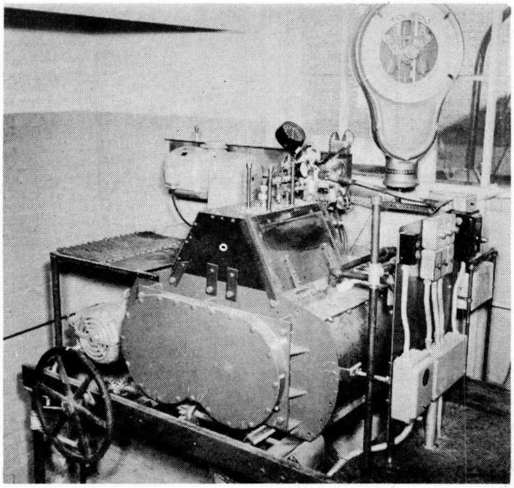

Figure 3. Pilot mixer equipped for foam asphalt mix operation.

The steam and binder controls may be interlocked so that steam is turned on first and shut off last. The steam in the nozzle serves another useful purpose in that it keeps the nozzle warm, thus minimizing the clogging of the nozzle between operations.

The foamed asphalt system can be adapted to any standard twin shaft pug mill type mixer and to other usual applications with a minimum of modifications that will be discussed as various applications are reviewed.

After a means of producing foamed asphalt under controlled conditions suitable and applicable to a wide variety of purposes was developed, the next step was to determine how the foamed asphalt performed in the mixing of bituminous mixes and to ascertain how foamed asphalt affected the properties of such mixes. A small 50-lb laboratory pug mill mixer for laboratory tests and a larger pilot plant 300-lb mixer for small scale mixing and field laying tests were adapted to foam asphalt mixing operations. Both of these mixers were fitted and equipped so that standard, atomized asphalt and bituminous slurry type mixes could be produced for comparative purposes.

The adaptation of these mixers necessitated the purchase of a small steam boiler to produce and supply the saturated steam required to both mixers. This boiler is the steam jenny type, fitted with a 60 gallon boiler, automatic electric fuel oil burner and all necessary safety devices. Steam pressures of this boiler can be regulated and automatically controlled between 5 and 100 psi (Figure 4). The pilot plant mixer, (Figure 3) was equipped with a variable speed motor drive for the asphalt pump to control the quantity of binder delivered to the nozzles. A two nozzle spray bar is used to introduce the binder into the mixer. All asphalt lines are electrically heated. On this unit the binder is measured in a weigh bucket from which it is pumped to the spray bar. The steam line from the boiler to the nozzles is equipped with an adjustable steam pressure regulator, an electric solenoid shut-off valve, a steam volume control needle valve and a steam pressure gauge. The mixer is also equipped with a water spray bar at the rear of the mixer to furnish water for wet slurry and soil stabilization mixes. The mixer also has interchangeable fluffing and kneading paddle tips. The small laboratory mixer is similarly equipped with the addition of a variable speed motor drive on the mixer shafts. The mixing speed of the shafts of the pilot plant can also be varied by changing the size of the drive shaft pinion. Standard, foamed asphalt, atomized asphalt, bituminous slurry and soil stabilization mixes can be produced with two mixers so equipped in the quantities needed both for laboratory and for field tests.

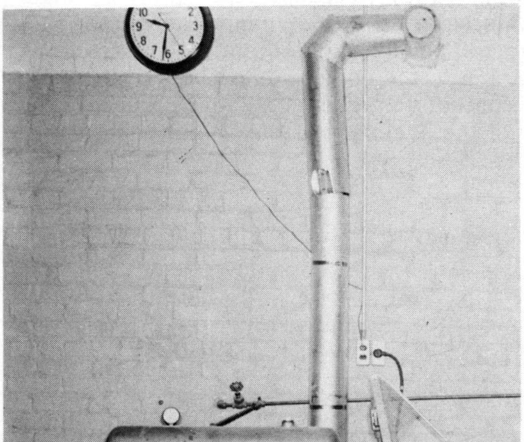

Figure 4. Small boiler unit for generating steam.

The next step in the development involved the production of various types of mixes to test the efficacy of the use of foamed asphalt in mixing procedure and the affect of foamed asphalt on the physical properties of such mixes. Included in the various mixes prepared and tested were: ungraded aggregate mixes, plant mix soil stabilization mixes, in place soil stabilization mixes, and also high type standard specification mixes.

UNGRADED AGGREGATE MIXES

The Bituminous Research Laboratory of the Engineering Experiment Station, Iowa State College, under the sponsorship of the Iowa Highway Research Board, recently completed the development of a mastic theory of design and a method of

producing bituminous paving mixtures utilizing local ungraded aggreates 1, 2. Since the present work is under the same sponsorship, the application of foamed asphalt in the production of mixes of this type was investigated first. Bituminous paving mixes using ungraded aggregates, similar to those used in the previous work, were therefore produced using foamed asphalt as the binder. These mixes were studied to determine whether or not the mastic theory of design was applicable to them. The physical properties of these mixes were determined and compared with those made by the earlier method.

The mixes were produced with the use of a discrete foam nozzle which emits the foamed asphalt in the form of separate, individual, small bubbles of binder. The mixer was equipped with an open grid type fluffing paddle tip. (Later it was found that the usual paddle tips can perform this function.) The purpose of this type paddle tip is to fluff and loosen or disperse the aggregate in the mixer during the mixing so that the bubbles of foamed binder may penetrate and contact all the particles of the aggregate. As each bubble of the binder enters the loosened and fluffed mass of aggregate and comes in contact with the aggregate particle the bubble bursts, forming a thin film of binder over the surface of the particle. When the bubble bursts the surface tension spreads the thin film of binder forcefully and rapidly over the surface of the aggregate. The modified surface tension of the binder when in the form of a bubble also provides natural forces which induce a high adhesion between binder and aggregate particle. It should be noted in comparing this method with the earlier method developed, that bubbles of binder are used in place of atomized droplets of binder, that bubble and aggregate are brought into contact only, rather than having a high speed impact between droplet and aggregate, and that the aggregate is fluffed in the body of the mixer rather than casting of aggregate into binder spray.

The materials used in these tests included blow sand, fine sand, pulverized loess, limestone dust as aggregates, and a 150 to 200 penetration asphalt cement as the binder. The gradation of the mineral aggregates was as follows:

TABLE 1

Total % Passing	Fine Sand	Blow Sand	Pulverized Loess 38% Clay	Limestone Dust
No 4 sieve	99	100	-	-
No 10 sieve	94	99	-	-
No 40 sieve	20	98	-	-
No. 60 sieve	-	-	-	98
No. 80 sieve	3	33	-	93
No. 100 sieve	-	-	-	90
No 200 sieve	1	4	100	65

These materials are essentially the same as those used in the previous work (1, 2).

Mixes containing various combinations of these aggregates with various binder contents were prepared for test. The mixes were prepared by placing the proper proportion of hot dry sand at about 400 F and dry dust at room temperature into the laboratory mixer and mixing for a few seconds to fluff materials in the mixer and to permit the dust to absorb some heat from the sand. The foamed asphalt cement was then introduced in the form of a discrete foam by the foam nozzle operating at a binder pressure of 50 psi and a saturated steam pressure of 60 to 70 psi. The mixing of a 25 pound batch required about 7 to 11 seconds. The temperature of the mixture discharged from the mixer was between 300 and 350 F. All mixes prepared were homogeneous, with all particles fully coated by thin films of binder and with a well formed mastic as desired.

Immediately after mixing, Hubbard-field stability test specimens, 2-in. in diameter and about 1 in. in height were prepared. These specimens were tested three days after forming for Hubbard-field stability at 140 F after 1 hour immersion in a hot water bath at 140 F. Void content determinations and freezing and thawing tests were also made on these specimens.

The results of these tests on the various mixes prepared are shown in Tables 2-6.

Mix proprtions are given as percent of total aggregate for aggregates and percent of binder added to total aggregates for the binder.

The results of these tests prove conclusively that bituminous mixes containing ungraded aggregates can be efficiently and successfully produced when foamed asphalt in the form of a discrete foam is used as the binder. The results of the tests also show that the mixes made in this manner also have very much higher stability and a much

TABLE 2

BLOW SAND 70%, PULVERIZED LOESS 30%

	Foamed Binder	Atomized Binder
8% Asphalt Cement		
Hubbard field stability	1650	1250
Voids, %	13 5	14
Resistance to freezing-thawing	Satisfactory	Satisfactory
9% Asphalt Cement		
Hubbard field stability	1600	1450
Voids, %	12.4	10 7
Resistance to freezing-thawing	Satisfactory	Satisfactory
10% Asphalt Cement		
Hubbard field stability	1650	1350
Voids, %	9.6	10.3
Resistance to freezing-thawing	Satisfactory	Satisfactory
11% Asphalt Cement		
Hubbard field stability	2050	1300
Voids, %	6 0	7 1
Resistance to freezing-thawing	Satisfactory	Satisfactory

TABLE 3

BLOW SAND 75%, PULVERIZED LOESS 25%

	Foamed Binder	Atomized Binder
7% Asphalt Cement		
Hubbard field stability	1450	1050
Voids, %	16 3	15 6
Resistance to freezing-thawing	Satisfactory	Poor
8% Asphalt Cement		
Hubbard Field Stability	1900	1300
Voids, %	14 2	13 6
Resistance to freezing-thawing	Satisfactory	Poor
9% Asphalt Cement		
Hubbard Field Stability	1600	1250
Voids, %	14 1	10.9
Resistance to freezing-thawing	Satisfactory	Satisfactory
10% Asphalt Cement		
Hubbard field stability	1500	1350
Voids, %	9 0	8.4
Resistance to freezing-thawing	Satisfactory	Satisfactory

TABLE 4

FINE SAND 80%, PULVERIZED LOESS 20%

	Foamed Binder	Atomized Binder
5% Asphalt Cement		
Hubbard field stability	1400	1300
Voids, %	11 7	11 6
Resistance to freezing-thawing	Fair	Poor
6% Asphalt Cement		
Hubbard field stability	2000	1650
Voids, %	9 7	9.0
Resistance to freezing-thawing	Fair	Poor
7% Asphalt Cement		
Hubbard field stability	1650	1500
Voids, %	5.9	6.6
Resistance to freezing-thawing	Satisfactory	Satisfactory
8% Asphalt Cement		
Hubbard field stability	1700	1350
Voids, %	3 7	4 7
Resistance to freezing-thawing	Satisfactory	Satisfactory

TABLE 5

FINE SAND 75%, PULVERIZED LOESS 25%

	Foamed Binder	Atomized Binder
6% Asphalt Cement		
Hubbard field stability	2400	1700
Voids, %	9 2	8.9
Resistance to freezing-thawing	Satisfactory	Poor
7% Asphalt Cement		
Hubbard field stability	2200	1200
Voids, %	7 1	8 3
Resistance to freezing-thawing	Satisfactory	Satisfactory
8% Asphalt Cement		
Hubbard field stability	1800	1000
Voids, %	4.6	4.5
Resistance to freezing-thawing	Satisfactory	Satisfactory
9% Asphalt Cement		
Hubbard field stability	2100	1400
Voids, %	1 7	2.7
Resistance to freezing-thawing	Satisfactory	Satisfactory

TABLE 6

BLOW SAND 70%, LIMESTONE DUST 30%

	Foamed Asphalt	Atomized Asphalt
6% Asphalt Cement		
Hubbard field stability	1950	-
Voids, %	14.5	-
Resistance to freezing-thawing	Satisfactory	-
7% Asphalt Cement		
Hubbard field stability	2600	1800
Voids, %	10 0	12.0
Resistance to freezing-thawing	Satisfactory	Satisfactory
8% Asphalt Cement		
Hubbard field stability	2350	1800
Voids, %	10.5	11 2
Resistance to freezing-thawing	Satisfactory	Satisfactory
9% Asphalt Cement		
Hubbard field stability	3500	2350
Voids, %	8 2	5.7
Resistance to freezing-thawing	Satisfactory	Satisfactory

greater general resistance to the effects of freezing and thawing than the same mixes prepared with the binder in an atomized form. There are other advantages of the use of foamed asphalt as the binder when compared with the use of the binder in an atomized form. The foamed asphalt process requires low pressures of 25 to 50 psi for pumping the binder, instead of the very high pressures of 300 psi and more required by the atomizing process. The need for high pressure piping is eliminated, smaller units of equipment can be used, power consumption for operation is greatly reduced, leaks in the system are minimized and operational safety is greatly enhanced.

Having demonstrated that bituminous mixes containing ungraded aggregates could be successfully produced with a binder in the form of a discrete foam, a study was made to determine if the same mixes could be prepared with the binder in the form of a concentrated foam. This study disclosed that these mixes can be prepared with the binder in such form but that mixing procedure must be altered.

The mixes utilizing the binder in a concentrated form of foam can be made in a standard pug mill mixer having the usual kneading paddle tips and operating at manufacturer's design speed. The binder is introduced as a concentrated foam by a properly adjusted foam nozzle operating at 25 psi binder pressure and 50 psi saturated steam

pressure. The mixing is done in a conventional manner. After placing aggregates into the mixer they are given a 5 to 10 second dry mix followed by the addition of the binder and a wet mixing for about 20 to 25 seconds. A total mixing time of about 30 seconds is required. It should be noted that no special paddle tips nor increase of mixer speed is required when a concentrated foam is used.

Bituminous mixes containing ungraded aggregates were prepared with the binder in the form of a concentrated foam. The mixes were uniform in nature with all aggregate particles coated with thin films of binder and the mix contained the desired mastic. Specimens were prepared and tested as before. The results of those tests were very much the same as those obtained from mixes in which the discrete foam was used.

In the process of this study it was also found that the fine aggregates need only be heated to 290 F and the pulverized loess or mineral filler can be used at air temperature when concentrated foam is used. When the discrete foam or atomized binder methods were used it was necessary to heat the fine aggregate to over 350 F to warm up the cold filler sufficiently for proper coating with binder.

This is a method of producing bituminous mixes containing ungraded aggregates in standard batch plants with little or no modification of operations and procedures other than introducing the binder in the form of a concentrated foam. All indications noted during the study are that this method is also readily adaptable to continuous mixer operation.

PLANT MIX SOIL STABILIZATION

Observations made during the mixing indicated that this method of introducing the binder in the form of a concentrated foam might be applied advantageously to soil stabilization. The use of the binder in the form of a concentrated foam in the preparation of plant mix soil stabilization mixes was investigated.

In the preceding work on the preparation of bituminous mixes containing ungraded aggregates the filler used to form the mastic was a dry mineral dust. Therefore the first series of tests conducted in relation to soil stabilization was made to determine whether or not an unpulverized or raw damp loess could be used as the filler.

The pilot plant mixer was used to prepare the mixes tested in this part of the study. This mixer is a 300-lb capacity, batch type, standard twin shaft pug mill mixer, equipped with conventional kneading paddle tips and operating at a shaft speed of about 90 rpm. The mixer is also equipped with a foamed asphalt system having two foam nozzles on the spray bar. The nozzles were adjusted to produce a concentrated foam of the binder when the system operated at 20 psi pressure for the binder and about 50 psi for the saturated steam pressure.

Tests were first made on mixes containing 75 percent fine sand and 25 percent raw loess by weight as aggregates, and 5 percent and 6 percent 150 to 200 penetration asphalt cement introduced into the mix in the form of a concentrated foam as the binder. The fine sand used in these mixes is the same as that used in previous mixes (Table 1). The loess is the same base material containing 38 percent clay, but in these tests it was used directly from stockpile, containing agglomerations and lumps as large as 3 in. in diameter instead of being processed and pulverized. Both materials were used at air temperature and contained some moisture. The materials were proportioned by weight in 150-lb batches containing 75 percent fine sand and 25 percent raw loess.

The proportioned aggregates were placed directly into the mixer. The mixing was started, and water was added to the materials in the mixer until the raw loess softened, agglomerations and lumps broke apart, and the loess was uniformly distributed throughout the mix. The quantity of water needed depended upon the initial moisture in the aggregates. It was found, however, that a total moisture content of about 8 percent in the mixer was sufficient to break down and distribute the loess. It was also found that about 30 seconds of mixing was required to secure a uniform mixture. As soon as a uniform mixture was secured, the binder, a 150 to 200 penetration asphalt cement at 300 F, was added to the mix in the form of a concentrated foam. Mixes containing 5 percent and 6 percent of binder by weight were produced. The time required to add the binder in this manner was about 10 seconds. Mixing was continued after the addition of

the binder for about 20 to 30 seconds to provide for the distribution of the binder throughout the mixture. The total mixing time per batch was about 60 to 70 seconds. Excellent mixes were produced of uniform character containing an evenly distributed mastic.

The water added to the aggregates during mixing serves several important purposes. It so softens the clayey materials or heavy soil fractions in the mix that lumps or agglomerations are broken up and the material can be distributed uniformly throughout the mixture. The water also separates the fine particles and suspends them in the water medium during mixing. These channels of moisture in the mix, particularly around the fine particles, provide paths through which the foamed binder can readily travel to coat all the mineral particles during mixing. Without sufficient water in the mixture satisfactory mixes could not be produced, but if the aggregates contain sufficient moisture no water need be added. If they do not contain sufficient water then water must be added, but water should be added carefully because excess water is as detrimental as insufficient water. The proper quantity of water for any mix combination of aggregates can be readily determined by a few trial batches.

Test specimens were prepared from these mixes and tested in the same manner as those of previous mixes. It should be noted that the curing time was three days prior to testing. The curing time is significant as will be noted later. The results of these tests are shown in Table 7.

The Hubbard-field stability test was used to compare the results of these mixes directly with the results of other mixes prepared by this method. Since the specimens were cured for only three days, to make direct comparisons, the specimens were still damp. The tests made after submerging the specimens in water at 140 F for 1 hour yielded only 600 to 650-lb stability. Specimens cured for 11 days prior to testing were much drier and yielded a stability of 1,100 lb. It seems that as the mix dries its stability increases and once dried it retains its higher stability.

About 3 tons of the mix containing 6 percent A. C., as shown in Table 7, was prepared and laid as a small field test area. The test was placed as a section of a roadway, 8 ft wide, 20 ft in length and 6 in. in depth, carrying about 400 cars a day. The mix laid in one lift 6 in. in depth spread easily and smoothly by raking. The mix was compacted readily by medium weight wobble wheel pneumatic rolling to a compacted depth of 5 in. The test pavement was opened to traffic 18 hours after laying. The behavior of the pavement was observed daily for about seven days. No settlement, ravelling, or rutting was observed, even after a heavy rain on the third day during this period. Slight scuffing of the surface was however noted which lead to the decision to seal the surface. The surface was sealed on the eighth day with a single layer sand seal. This seal consisted of a prime coat of 0. 1 gallon Mc-0, followed by 0. 2 gallons, 150-200 pen. A. C. and 20 lb of coarse sand per sq yd. This pavement laid early in September 1956 has been performing excellently for the past four months. Weather conditions during this period have varied from 90 F and 10 F with heavy rains, snow and ice on the surface.

In preparation for in-place soil stabilization studies of this method, the material removed from the roadway in the above test area was tried in plant mix operations. The existing roadway was surfaced with power house cinders laid about 1½ to 2 in. thick upon a heavy clay soil. The upper 4 in. of the material removed from the roadway, consisting of 2 in. of cinders and 2 in. of soil, were used in this test. The gradation of this combined material was as follows:

Sieve	Total Percent Passing
3/8	93
4	82
10	68
40	46
80	34
200	26

In preparing these mixes, the cinder-

TABLE 7

MIX. 75% FINE SAND, 25% RAW LOESS

Moisture content during mixing 8%	6% A C.	5% A C.
Hubbard field stability 77 F dry	3000	3100
140 F dry	1650	2200
Standard 140 F wet	600	650
% voids in compacted mixture, not corrected for moisture	12%	14%
Unit weight, pcf	148	151
Resistance to freezing-thawing	Good	Good
Max volume change	4%	3 6%

clay combination was placed in the mixer and water was added in a quantity sufficient to distribute the clayey soil uniformly throughout the mixture. Then 6 percent of 150-200 pen. A. C. was added in the form of a concentrated foam and mixing continued for 30 seconds. Since this mix contained coarse particles Marshall-stability test specimens were prepared. The results of these tests were as follows:

TABLE 8

Moisture in mixture	8%
Marshall stability 140 F wet	480 lb
Voids in compacted specimen	16.7
Resistance to freezing-thawing	Fair
Unit weight per cu ft	142 lb

Similar mixes were produced in which 20 percent of raw loess was added to the cinder clay soil combination. The mixes were prepared and tested in the same manner as the cinder clayey soil mixes. The test results are shown in Table 9.

Analysis of these test results indicates that some bituminous soil stabilization mixes can be produced by this method which closely approach Marshall stability criteria for asphaltic concrete. These encouraging results lead to a study of adapting this method to in-place soil stabilization.

IN-PLACE BITUMINOUS SOIL STABILIZATION

The applicability and the efficacy of the use of a bituminous binder in the form of a concentrated foam in in-place bituminous soil stabilization was tried and tested on a Seaman-Andwall Pulvi-Mixer, stock model D. S. 47 having an 8 ft wide hood assembly. This machine was secured by the Bituminous Research Laboratory for research purposes through the courtesy of the Seaman-Andwall Company of Milwaukee, Wisconsin.

Since this machine was a standard model and only on loan to the Laboratory, it was necessary that it be adapted to the foamed binder process with as little modification of the base unit as possible. The equipment necessary for this adaption included a small steam boiler to furnish the steam required for foaming the binder, a spray bar equipped with foaming nozzles at the assembly hood, and such piping, fittings, and controls as were necessary to convey the steam and binder to the spray bar.

The steam boiler used was a 60 gallon capacity steam jenny type fired by an automatic pressure controlled electric fuel oil burner. Steam pressure of this boiler could be automatically controlled at any pressure between 5 and 100 lb. This boiler was mounted on temporary steel bracket supports at the front end of the mixer (Figure 5). A small motor generator set was mounted on the running board of the mixer to supply the power needed to operate the electric fuel oil burner. Two main steam lines, each $\frac{3}{4}$ in. in diameter and insulated, were installed to convey steam from the boiler to the spray bar. One line, fitted with suitable operating controls for controlling the pressure and volume of the steam, was used to furnish steam to the foam nozzles. The other line was used to furnish steam to heat the steam jacketed spray bar.

The spray bar installed just in front of the hood assembly consisted of eight 2-in. ID steam jacketed tee fittings bolted together with one small steam jacketed straight section to form a continuous spray bar spanning the width of the hood assembly (Figure 6). Each tee fitting of the spray bar was equipped with a bituminous foam nozzle (Figure 7). The spray bar was so adjusted and positioned that the eight nozzles sprayed a uniform spread of foamed binder in front of the cutter and mixer

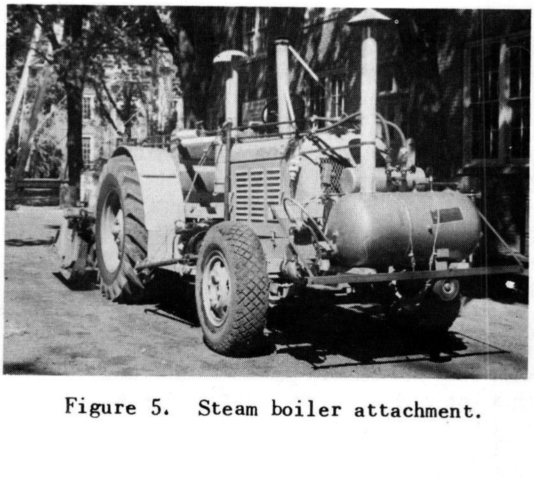

Figure 5. Steam boiler attachment.

TABLE 9

	5% A. C.	6% A. C.
Moisture in mix	8%	8%
Marshall stability 140 F wet	500	460
Flow	16	21
Voids in compacted mixture	15.1	15.5
Resistance to freezing-thawing	Fair	Fair
Unit weight	148	142

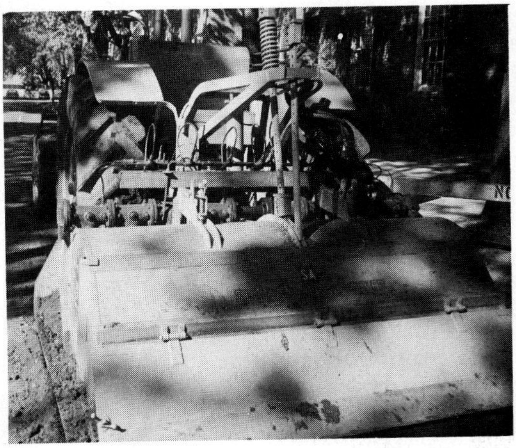

Figure 6. Spray bar attachment.

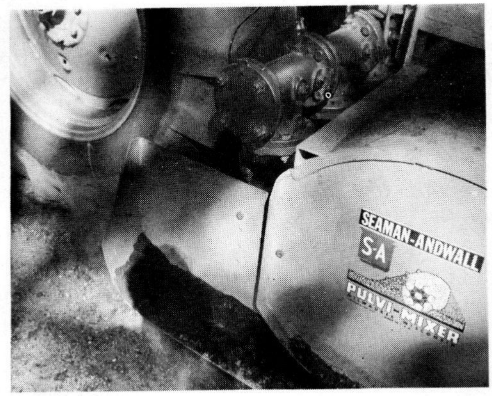

Figure 7. Spray bar showing nozzle for foaming the asphalt.

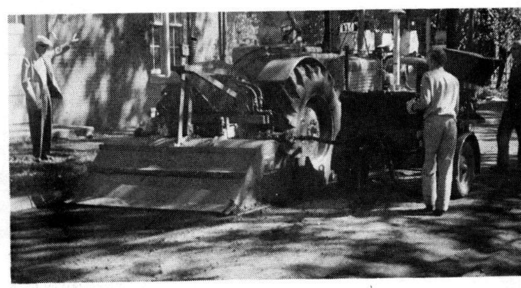

Figure 8. Stabilizer in operation.

blades of the hood assembly. The main steam lines from the boiler were connected to two steam manifolds, one of which distributed saturated steam to the nozzles, and the other steam to the steam jacketed sections of the spray bar. Steam operating pressure and volume controls on the main steam line carrying steam to the nozzles were placed within easy reach of the operator in the driver's seat.

The bituminous binder used in the operation was heated in a 160 gallon asphalt heater kettle. This kettle was towed alongside the mixer by an outrigger tow bar temporarily mounted on one side of the mixer. The binder was pumped from the kettle to the spray bar by a gasoline engine drive asphalt pump mounted on the kettle. A flexible metal hose connected this pump to the spray bar (Figure 8). Operation of binder controls was done manually by signal from the mixer operator. The mixer and asphalt supply kettle moved forward in unison during in-place soil stabilization operations.

The operation of the Pulvi-Mixer, adapted in the manner described to the use of a foamed bituminous binder, was tested on a section of test road 24 ft wide and about 250 ft in length. The surface of the test area consisted of a layer of power plant cinders about $1\frac{1}{2}$ to 2 in. thick laid upon a natural heavy clayey soil. A layer 4 in. deep consisting of approximately 2 in. of cinders and 2 in. of soil was stabilized in these tests. An average gradation of the mixture of these materials is given in the preceding section on plant mix soil stabilization. Moisture content of the road material varied from 6 to 16 percent during the tests, as will be noted, due to weather conditions. Two types of binder were used, an 85 to 100 penetration asphalt cement and a 150 to 200 penetration asphalt cement. Both types were heated to 300 to 330 F during application.

Since the materials in the road were stratified, it was deemed desirable that a mixing and blending pass be made prior to application of the binder. This pass served to loosen the layer of soil to be stabilized, to blend and mix it thoroughly and uniformly, and to break up clay agglomerations prior to stabilization. This was done prior to each run. In this preliminary pass the cutting blades in the hood assembly were set to a depth of 4 in. Each pass yielded about a 6-in. depth of loose mixed and blended material.

The application of the binder during the soil stabilization pass was made in the following manner: The Pulvi-Mixer was moved into position at one end of the mixing and blending pass, and the hood was lowered into position. The cutting blades were set to mix the full depth of loose material. Steam pressure of about 65 psi at the boiler was

reduced to about 40 psi by the controls and turned on to check if all foam nozzles were functioning properly. Then bituminous soil stabilization was started. As soon as the mixer began moving forward the asphalt was turned on to the spray bar. During the soil stabilization pass the mixer travelled at a speed of 40 ft a minute. This was the slowest speed at which this machine could be operated. The binder was shut off a few feet ahead of the end of the run to permit the spray bar and nozzles to drain. As soon as this drainage was completed, the steam was shut off. Due to the speed of the mixer and the limited capacity of the asphalt pump on the kettle, it was found that only 1 percent of binder could be applied at each pass. It was also noted that under these conditions no asphalt pressure was developed at the nozzles. The nozzles functioned satisfactorily under this condition. To introduce the desired quantity of binder, about 6 percent, several successive soil stabilization passes had to be made. This, however, served a useful purpose, because the characteristics of the mix with increasing quantities of binder could be observed.

The test road was constructed in three 8-ft wide parallel and adjacent lanes. The first outer lane was started by making a blending and mixing pass with the Pulvi-Mixer. Soon after this pass was made, an unforecast shower arrived and work was stopped. Then it continued to rain for two days for a total rainfall of 4 in. This rainfall thoroughly saturated the loosened material and the subgrade in this lane. When work was again started, it was found that the soil contained 24 percent moisture. Consequantly several aeration passes were made on successive days to dry out the soil. Bituminous soil stabilization was started when the soil moisture was at 16 percent. Four stabilization passes were made, introducing 4 percent of A. C. The binder was uniformly distributed in the mix which was somewhat spongy. Nevertheless it rolled well under a pneumatic roller and compacted tightly. In a few places where subgrade was still saturated the pavement showed subgrade failure under traffic. After the subgrade had dried somewhat, two additional stabilization passes were made, adding 2 percent of binder, raising the total to 6 percent. Moisture content in the paving at this time was about 6 percent. This mixture rolled very well and compacted tightly. It showed no displacement other than a slight scuffing under traffic. The binder used in this lane was 150 to 200 penetration asphalt cement. The other outer lane was treated with 85 to 100 penetration asphalt cement. At the time of treatment soil moisture was about 8 percent. The first mixing and blending pass was followed by successive stabilization passes applying 6 percent binder to the soil. An excellent uniform mix was secured. Initial compaction was made with two passes of a Jackson vibrating compactor. Good compaction was secured. The center lane was processed in the same manner as the second outer lane. Soil moisture in this lane was about 6 percent, and 150 to 200 penetration asphalt cement was used as the binder. Compaction was secured by two passes of the Jackson vibratory compactor, followed by pneumatic tire rolling.

The test area was opened to traffic on each lane as it was completed. Behavior was observed under traffic for about a week. During this period no displacement in any of the lanes was noted. A slight surface scuffing, however, did occur, and to prevent further scuffing of this nature the entire test area was sealed. One half was sealed with a single layer sand seal consisting of a prime coat of 0. 1 gallon per sq yd of MC-0 cutback followed by 0. 2 gallons per sq yd of 150 to 200 penetration asphalt cement covered by 20 lb per sq yd of coarse sand. The other half was sealed with Schlamme (3) applied at the rate of about 8 lb per sq yd, giving a layer about ⅛ in. in thickness. The paving in the test area has given excellent service during the past four months up to the time of this report. Traffic averages about 400 cars per day, and weather during this period has been comparatively severe, fluctuating between 90 F and 10 F in temperature and with heavy rains, sleet, freezing rain and about 4 in. of snow. The pavement is tight, sheds water readily, and shows no distress of any type.

Further tests with this machine in other areas with other types of soil had to be discontinued due to cold and inclement weather. It is expected that tests will be resumed early next spring. The work completed, however, has shown that the use of a foamed binder can sucessfully and effectively stabilize a heavy soil in an in-place soil stabilization operation. It has also shown that it can handle cinders, one of the most difficult materials to stabilize with a bituminous binder.

STANDARD SPECIFICATION MIXES

The knowledge and experience gained in the preceding studies led to a study of the use of foamed binder in conjunction with standard specification mixes. The question here was whether the foamed binder could be used with cold moist aggregates in the preparation of these mixes.

In this phase of the work, aggregates secured from an actual construction job under Iowa State Highway Specification were used. The gradation of these aggregates blended for the mix was as follows:

TABLE 10

BLEND OF ¾-⅜ STONE, 30%; PREBLENDED SAND 35%; CHIPS, 35%

Sieve No.	Total % Passing	Iowa Specifications Type A
1 in.	100	98-100
¾ in.	99	98-100
½ in.	92	-100
⅜ in.	81	67-87
No. 4	60	47-68
No. 8	46	37-55
No. 30	25	19-34
No. 50	18	13-26
No. 100	10	6-
No. 200	6	3-10

A sample of the Type A asphaltic concrete mix was also secured from this construction job and tested, using the Marshall stability test. This test was used for comparative purposes to correlate this study with previous and future studies carried on in the laboratory. The results of this test are shown in Table 11.

The first sequence of tests was made using cold damp aggregates at 70 F and containing about 3 percent moisture. Mixing was done in the laboratory mixer with standard kneading paddle tips in the following manner: Proportioned aggregates were placed into the mixer and mixed for 10 seconds, then 7 percent of an 85-100 penetration asphalt cement in the form of a concentrated foam was added, followed by a 30 second wet mix. The total mixing time was 47 seconds. In this mix an excellent mastic was formed with the fine aggregate and dust particles thoroughly and uniformly coated, but the coarse particles were only partially coated. When 150 to 200 penetration asphalt cement was used as the binder in this mix an improved coating of coarse particles was obtained. When the moisture in the aggregates was raised to 8 percent, improved coating of the coarse particles was also secured.

TABLE 11

TYPE A ASPHALTIC CONCRETE CONSTRUCTION SAMPLE

% asphalt cement	6.5
Marshall stability, lb	1260
Flow	12
Unit weight, pcf	142
Percent voids	7.1

The second sequence of tests made utilized aggregates dried and heated according to specifications. The mix was prepared in the same manner as those in the first sequence. Excellent mixes were secured which produced test results equal to those of the construction mix control. This sequence of tests disclosed that the foamed binder method can be applied successfully to standard mixes, mixed in the conventional manner in regular pug mill mixers, in which no special paddle tips or mixer speed changes are required.

A third sequence of tests was conducted to determine the limiting effects of the temperature of the aggregates. Mixes were made with the temperature of the aggregates reduced step by step. The character of each mix was carefully observed. It was noted that at aggregate temperatures of 180 F and above excellent mixes were secured. When the temperature was lowered to 160 F the coarse aggregate particles were not wholly coated with binder. Mixes made with the temperature of the aggregates at 180 F and 200 F were tested. The results of these tests are shown in Table 12.

TABLE 12

Aggregate temperature	180 F	200 F
% asphalt cement content	6%	7%
Marshall stability	610	700
Flow	8	10
% voids in compacted specimen	8	5
Unit weight, pcf	138	138

Analysis of the results of these tests confirms the effect of aggregate temperature upon some of the physical properties of the mix when asphalt cements are used as the binder. It was however noted from

experience in previous work that the effects of aggregate temperature are not nearly as great when the binder is applied in the form of a concentrated foam as it is when the binder is applied in either liquid or atomized droplet form. This characteristic of a foam binder in relation to aggregate temperature can have a material effect upon increasing plant production. Since the output capacity of most asphalt plants is limited by its drier capacity, any increase in drier capacity by reason of lowered aggregate temperature required would materially increase plant production.

CONCLUSIONS

In this research work the feasibility of efficiently and effectively producing a foam of a bituminous binder in several forms has been studied and the applicability and the efficacy of such foamed binders in bituminous paving mixtures and in bituminous soil stabilization has been investigated. Although the work was somewhat exploratory in nature, a mass of significant data and results of tests have been compiled from which many specific and definite conclusions may be drawn.

1. The study disclosed that a bituminous binder can be efficiently and effectively foamed in several forms. Special foaming nozzles were developed and designed, together with necessary adjunct apparatus, that can instantaneously create the character of foam desired at the time and place required. The foam can be introduced into a mixture in the manner and quantity required.

2. The physical properties of a bituminous binder can be temporarily modified without altering the chemical constitution of the binder by foaming the binder. The viscosity can be lowered materially to provide easier and more uniform distribution of the binder during mixing. The lowered viscosity increases the plasticity of the mixture at lower temperatures during placing or laying. The viscosity is restored to normal during compaction of the mixture, permitting it to set rapidly. The surface tension of the binder is so modified that coating of the aggregate is accomplished more readily, and improved adhesion between binder and aggregate is attained. Since the binder is in the form of a bubble rather than a liquid thin films of binder form on the aggregate surface merely upon contact, regardless of the size of the aggregate particle.

3. Bituminous mixes containing local ungraded aggregates can be produced more readily and safely by this method than by any other method studied and investigated in this or any other previous research projects conducted at the Bituminous Research Laboratory. When foamed binder is used, higher strengths, greater resistance to freezing and thawing, and other desirable properties are obtained than by any other method investigated. When a foamed binder is used the aggregates need not be heated to as high a temperature as that required by the atomized binder method to obtain satisfactory mixes.

4. Bituminous mixes containing local ungraded aggregates can be produced by the foamed binder method in standard twin shaft pug mill mixers without any change of mixer paddle tips or modification of mixing procedure.

5. Plant mix soil stabilization mixes can be produced readily and effectively without need of dry pulverization of fine fractions and with asphalt cement as the binder when the foamed binder method is used. Breakdown of agglomerations or lumps of fine or clayey fractions is achieved by the addition of the proper quantity of water prior to the addition of the foamed binder. The water also assists in the uniform distribution of the foamed binder throughout the mix. Mixing of this type of mixture can be accomplished in standard conventional mixers.

6. The use of the foamed binder method is readily and effectively applicable to in-place soil stabilization operations, using commercially available equipment. When reasonable soil moisture control is exercised, excellent mixes having the binder uniformly distributed throughout the soil can be obtained. Soil stabilization mixes containing heavy clayey soils and 6 percent of 150 to 200 penetration asphalt cement can be produced by this method. The mixes possess high stability, good resistance to freezing and thawing, good waterproof character, and other desirable properties.

7. Standard specification high and medium type asphaltic concrete mixes can also be produced by the foamed binder method. Such mixes have physical properties equiva-

lent to the same mixes made by conventional means. Mixing time can, however, be reduced and still secure uniform distribution of the binder throughout the mixture. Aggregate temperatures may also be somewhat lowered in high type, and may be considerably lowered in medium type asphaltic concrete mixes without adversely affecting the physical properties of the mixture when the foamed binder method is used. Plant capacity can be increased by producing mixes using the foamed binder method.

8. The foamed binder method can be used in conjunction with either batch type or continuous type mixers.

FURTHER WORK

The work concerning foamed bituminous binders up to this time has been aimed toward determining their application to and their efficacy in the production of a variety of bituminous paving and soil stabilization mixes. With this phase of the work nearing completion, attention is being directed toward the details of optimums of design and to the control of the wide variety and numerous types of bituminous mixes which can be produced by utilizing the foamed binder method.

PATENTS

The new developments made or discovered in the prosecution of this work have been assigned to the Iowa State College Research Foundation. The Iowa State College Research Foundation has filed patent applications covering the method; the apparatus, including the nozzles; the use of the various forms of foamed binder and its application to the various types of bituminous mixes. Patent applications have been filed in the United States and Germany, and may also be filed elsewhere as deemed desirable.

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