Triaxial Shear Strength Characteristics Of Some Sand-Asphalt Mixtures

K. O. ANDERSON, R. C. G. HAAS, and A. D. LAPLANTE
Respectively, Associate Professor of Civil Engineering, University of Alberta; Lecturer, School of Engineering, Carleton University; and Instructor, North Alberta Institute of Technology, Edmonton, Alberta

This investigation, which arose from a considered need for more work of a fundamental nature in asphalt stabilization, determined strength relationships of cutback asphalt, emulsified asphalt, asphalt, hot-mix and foamed asphalt mixtures by triaxial compression testing of cured and water-immersed specimens.

The results show that for the fine, uniform and rounded quartz sands used (99 percent passing No. 40 sieve with a uniformity coefficient of approximately 2.00), the foamed asphalt process results in superior shear strengths of cured specimens, compared to the other processes. However, immersion causes a considerable loss in cohesion resulting in strengths similar to those of immersed cutback or emulsified asphalt specimens, although alternate cycles of curing and immersion do not significantly affect the final cured shear strengths of foamed asphalt specimens. It is also shown that at the same estimated bituminous film thickness, the addition of a limited amount of fines passing a No. 50 sieve size results in increased cured cohesive strengths.

It is postulated that the higher strengths of the cured foamed asphalt mixtures are due primarily to apparent cohesion resulting from surface tension forces in the water phase, the magnitude of which is related to the uniformity and thickness of asphalt films coating individual sand particles.

•SOIL STABILIZATION by incorporation of admixtures has been the subject of many research projects, particularly in recent years. At present, it is probably being investigated by practically all agencies concerned with pavement design and construction. The extent of investigation may range from comprehensive reviews of published literature, through long-term performance studies of existing facilities, to intensive laboratory research projects on specific facets of the stabilization process. Census reports of current highway research projects (4, 17, 18, 19) indicate the broad overview of such projects under way in North America; some selected papers (11, 28) indicate the position elsewhere.

Until recently, the major portion of the work in asphalt stabilization has been of a practical nature to arrive at a set of empirical design standards and construction procedures suitable usually for a particular locale (16). Increased efforts have been made during the past few years to investigate soil stabilization on a more scientific basis and to provide more information on fundamental mechanisms. The method of evaluating these mechanisms and comparing strength relationships often lies in the triaxial compression test, although the empirical values of cohesion and angle of

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internal friction obtained (using the Coulomb equation to represent internal stability) are merely convenient terms for discussing the shearing strength of a material. It must be realized that the gap between evaluating and understanding fundamental mechanisms and transferring them to rational methods of pavement design is still very large and will be bridged only by continued extensive research.

The objective of this investigation, which was part of a continuing series of investigations on stabilization of highway materials sponsored by the Joint Highway Research Program in Alberta, was to compare and analyze shear strength relationships of a uniform fine-grained sand stabilized with a cutback asphalt, an asphalt cement and an emulsified asphalt. The major variables were (a) the method of introducing the asphalt to the sand-water mixture with special emphasis on the foamed asphalt process; (b) the comparison of shearing strengths of cured samples of sand-asphalt; (c) the effect on shearing strength of soaking cured samples; and (d) the effect on shearing strength of varying the sand gradation by recombining with fractions of the sand itself.

To obtain as definitive results as possible and to provide some measure of quantitative and qualitative comparisons with other work, many conditions of testing were made constant. Unfortunately, these conditions of testing, although consistent with other work at the University of Alberta, were of necessity arbitrary in nature and this, of course, is one of the major limitations of an investigation of this type.

Phase 1 of the investigation deals with cutback asphalt, hot-mix and foamed asphalt stabilization of the sand; Phase 2 deals with an overlap of the foamed asphalt stabilization on a sand from the same source but slightly altered gradation, emulsified asphalt stabilization, and the effects on strength characteristics of foamed asphalt-stabilized sand with varying gradations. Phase 2 was started when Phase 1 was about half complete, and although it was intended to answer some of the questions posed by Phase 1, as well as to continue some of the work of Phase 1, time limitations prevented these goals from being completely realized. For the sake of consistency, the methods of compaction, curing, soaking, and triaxial testing were constant through both phases.

SAND-ASPHALT STABILIZATION

In the stabilization of cohesionless soils with asphalt or other bituminous materials, the admixture serves a dual purpose of binding soil particles together to give cohesion to the mass and of waterproofing the mixture. The effectiveness of asphalt as a stabilizing agent is limited by the difficulty of distributing it uniformly throughout the soil mass and by its inability to adhere to wet soil particles. In addition, the asphalt-soil bond is sensitive to destruction by water. Thus, the degree to which asphalt will satisfactorily stabilize a soil depends on such factors as amount of water present during mixing, type and duration of the mixing process, temperatures involved, physical properties of the soil and the asphalt, the compactive effort used, the amount of water present during compaction, and the climatic conditions to which the stabilized mass will be subjected.

The distribution of asphalt throughout the soil mass is facilitated by modifying the asphalt physically to increase its fluidity or by decreasing its viscosity by introducing it into the soil mass in the form of a foam. Increased fluidity is accomplished by diluting the asphalt with an evaporable cutback or solvent, by emulsifying the asphalt in water, or by heating the asphalt to make it fluid. The foamed asphalt process, a relatively recent development, is discussed subsequently in more detail.

In the process of development of the basic principles involved in asphalt stabilization, two major concepts regarding the performance of the bituminous binder and mineral constituents have been proposed (9). The plug theory, which contends that the capillaries in the soil mass are plugged with asphalt to prevent movement of water, and the intimate mix theory, which contends that the individual soil particles are coated with a thin film of asphalt, thereby preventing attack by water, are probably both true to a certain extent. It seems logical that a compromise of both holds for a good many cases.

Influence of Film Thickness on Shearing Strength

The cohesion imparted to a sand by mixing it with asphalt is dependent on the thickness of the asphalt film and the viscosity of the binder. Csanyi (5) has indicated that

the most significant factors affecting film thickness are adhesion between the aggregate and the binder, the temperature of both the particle and the binder, the viscosity, the cohesion and the surface tension of the binder at the temperature of the mixture, and the quantity of binder present in the mix. Goetz (12), using the triaxial test as a measure of stability, showed that as the asphalt content (and film thickness) increased, the stability of the mix increased to a maximum and then decreased. Mach (22), using a tension test with metal plates cemented together with bitumen, demonstrated the existence of an optimum film thickness varying from 4.5 to 7.0 microns for different binders; he found that the optimum film thickness increased with increasing viscosity of the binder and indicated that the mineral filler could become part of the film between sand particles. Douglas and Tons (8), using the Smith triaxial test to measure shear strengths of bituminous mastic concretes, found cohesive strengths of 103 and 25 psi for estimated film thickness of 5 and 7 microns, respectively, although the respective friction angle values were 36 and 10 degrees.

Thus, generally speaking, it appears that too thick a film merely lubricates the aggregate particles. For this reason, it would appear desirable from the viewpoint of obtaining high shearing resistance to have as thin a film as possible, using as viscous a binder as possible. However, too little asphalt may not coat all the particles and thereby actually decrease stability and durability.

Influence of Filler on Shearing Strength

Rice and Goetz (26), in investigating the suitability of Indiana dune, lake and gravel-pit sands for low-cost sand-bituminous pavements, found that particle size, shape, texture and grain size distribution affected both the cured and immersed compressive strengths. They found that fillers affected strengths to varying degrees, depending on the amount and types used, but generally, unconfined compressive strengths increased with increasing percentages passing the No. 200 sieve. In addition, the optimum asphalt content varied for various filler-binder ratios and generally increased ·ith increasing percentages of filler.

Endersby and Vallerga (10) found that increased surface area can result in increased contact areas between particles, thereby influencing the strength characteristics of bituminous concrete.

Griffith and Kallas (13) found the effect of filler particle shape on the stability of mixes to be greatest when the fine fraction (minus No. 8 sieve size) is between 40 and 60 percent of the total weight of the mix. Kallas, Puzinauskas and Krieger (20) found that the stability of mixes increased as the amount of filler was increased. They also found that the stability of paving mixtures increased with increasing viscosity of the filler asphalt binder; viscosity, in turn, increased with increasing filler-binder ratios.

Influence of Mixing Water and Mixing Operation

The importance of having sufficient water in a mix for good distribution of asphalt and lubrication during the compaction process has been recognized for some time. Benson and Becker (2) found that the contact angle between the asphalt and the mineral particles is decreased by adding water, thus permitting easier spreading of the asphalt throughout the mix. In addition, it seems reasonable to assume that water in the mass separates particles and provides a fluid medium through which the asphalt globules or bubbles may easily pass throughout the soil void spaces. Thus, water content can usually be increased over a wide range above some minimum necessary for good distribution of asphalt; however, too high a water content can lead to compaction and curing difficulties.

The water content to use for good distribution of asphalt and for compaction requirements is not always that which gives desirable stability properties. Since the percentage of water required to produce maximum strength, maximum density, minimum total moisture absorption, and minimum expansion is different for each of these properties, Katti et al. (21) suggested the selection of a compromise moisture content for mixing at this water content, which was approximately the same as the optimum moisture content for total maximum dry density; each of the desirable properties will

be at a minimum variance from their optimum value. In our preliminary work with cutback asphalt-sand mixtures (25), support was found for this relationship. Although Katti found maximum strength coincident with maximum density, as did Pennell, Herrin (15) reported that there are indications that high strength is not related to high unit weight in soil-asphalt mixtures. Thus it is obvious that this aspect of soil-asphalt stabilization requires considerable work to provide conclusive answers for a wide range of conditions and materials.

The fact that the mixing operation influences the properties of a bituminous mixture has been known for some time. However, the importance and magnitude of these effects have often been unappreciated and underestimated, especially for soil-bituminous mixtures. Optimum mixing times for a particular soil, a particular asphalt and a particular water content have been investigated by Benson and Becker (2) and Endersby (9). They found that mixing times longer than 1 to 2 minutes produced intimate mix conditions where groups of soil particles were further broken and the asphalt becomes too thinly distributed for good waterproofing. In addition, the mixing water exerted a much greater influence on mixing time than did the asphalt content with higher water contents. However, no satisfactory mechanical evaluation or appraisal method exists at this time. Thus, considering the many variables that affect the mixing operation and unless the particular effects of the mixing operation are being investigated, mixing operations within a particular group of tests should probably be made as constant as possible. The factor of soil particles breaking down with too long a mixing time is probably not a very important consideration for quartz sands similar to those used in this investigation.

Asphalt Stabilization Processes

Cutback asphalt stabilization consists essentially of three steps: (a) mixing the cutback with the soil at some water content; (b) compacting the mixture, either immediately after mixing or after some period of drying back, to provide initial stability; and (c) curing the mixture by allowing evaporation of water and solvent. As the water and solvent evaporate from the mix, either before compaction or after compaction during the curing process, it becomes possible for the asphalt to spread out and adhere to the mineral particle surfaces. This wetting-out enables the asphalt to distribute itself more uniformly throughout the mass, depending considerably on its fluidity which in turn depends on the rate of evaporation of the solvent. The amount of water required for cutback asphalt stabilization depends on the soil used, the cutback asphalt used, and the stability and durability properties required.

Emulsified asphalt stabilization has also been successfully practiced in certain areas of the United States for some years, as reported by McKesson (24). The emulsions primarily used are the slow setting type. In addition, the importance of emulsion electrical charge for the adhesion of emulsified asphalt to mineral aggregates, insofar as the uses of cationic and anionic emulsions are concerned, has been demonstrated by such investigators as Borgfeldt and Ferm (3).

Penetration-grade asphalts have been successfully used to stabilize clean sands, such as on projects in Manitoba and Minnesota, as described briefly by Sharpe (27). However, the usual procedure of hot mixing makes this method of introducing asphalt into a soil mass for base stabilization prohibitive, except possibly for some very specialized cases. The exception is the foamed asphalt process which does use an asphalt cement with a cold wet mix.

The foamed asphalt process described by its developer, Csanyi (7) consists essentially of introducing steam, at controlled temperature and pressure, into a heated penetration-grade asphalt cement. Extrusion through a special nozzle causes the asphalt to be emitted in the form of a foam, the character of which is controlled by the pressures used. Foaming does not alter the asphalt chemically but changes its viscosity and consistency by producing bubbles of high surface tension that have high adhesive and cohesive properties. The viscosity is materially lowered to permit the binder to be used at much lower temperatures than the liquid binder. When the bubbles come in contact with aggregate particles, they burst and spread rapidly and forcefully over the surface of the particle. Csanyi states:

> 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 the aggregate. (23)

The increased wetting power seems logical because of the ready-made thin film of asphalt cement with stored energy available to assist in coating particles as the bubble breaks. However, it is considered that more information on surface and interfacial tensions of the binder and aggregate is necessary to substantiate the concept of displacement of surface moisture on the aggregate.

The foamed asphalt process itself may be contrasted to a more conventional process where the binder apportioned for filling voids is a free agent during mixing and acts as a lubricant to permit particles to roll around and pick up their coatings. Thus, it seems reasonable that in the conventional process film thickness and uniformity would vary considerably in any individual particle and from particle to particle. However, the foamed asphalt process could be somewhat unique in that the particles are coated with very thin and uniform films of binder. If these films are of the same thickness as adsorbed films, they would behave more rigidly than thicker films and, thus, an apparent internal friction could be developed. This internal friction would also depend on the ratio of contact area to surface area of the particles, which would be considerably greater in a mix of uniform film thickness. In addition, more uniform film thicknesses would allow for a closer arrangement of particles, or higher density, with resultant greater contact area. It is further possible that the condition of thin and uniform films could result in asphalt capillary tension forces to some degree.

These postulations about uniformity and thickness of films in the foamed asphalt process convince us that very high apparent strengths could be developed in these mixtures from drying out of the water phase, mainly as a result of the small and uniform void spaces developed. In other words, these void channels would have very small radii of curvature to result in very high capillary tension forces in the water phase.

MATERIALS

The soil used for both phases of the investigation was a fine, rounded, poorly graded quartz sand obtained from a pit near Stony Plain, Alberta. It would be classified as an A-3 or an SP type soil. Microscopic examinations revealed an almost complete absence of clay-size particles.

The actual gradations of the sand varied somewhat between Phase 1 and 2 of the investigation in that the Phase 1 material exhibited a slightly better gradation with more fines. The gradation of Phase 2 sand was altered by adding varying amounts of mineral filler sieves from the original sand. Detailed sand properties are given in Tables 1 and 2.

The MC 3 cutback asphalt used in Phase 1 had a specific gravity at 60 F of 0.972, a residue of 79.0 percent and a residue penetration at 77 F of 155. The 150-200 penetration asphalt cement used for hot mixes and foamed asphalt mixes of Phase 1 and for foamed asphalt mixes of Phase 2 had a specific gravity at 60 F of 1.029 and a penetration at 77 F of 153. The SS-1 emulsified asphalt used in Phase 2 showed a percent residual asphalt of 62.0 and the residue penetration range of 150-200.

TESTING PROGRAM AND PROCEDURES

The main testing program of both phases of the investigation consisted of triaxial compression tests on sand-asphalt specimens cured for 7 days at 100 F, cured for 7 days at 100 F and then immersed for 14 days at room temperature, or cooled for 24 hr (for the hot mixes) at room temperature.

The following test conditions and procedures were constant unless otherwise noted:

TABLE 1

SAND PROPERTIES

Description	Phase 1	Phase 2
Source	McGinn Pit[a]	McGinn Pit[a]
AASHO classif.	A-3[b]	A-3[b]
Sp. gr.	2.67[b]	2.67[b]
Std. AASHO		
Density (pcf)	104.0[b]	103.2[b]
Opt. w/c	15.0[b]	13.6[b]
Grain sizes (% <)		
No. 10	100	100
20	100	100
40	99	99.6
60	76	61.0
80	-	-
100	24.7	15.5
200	8.1	5.7
D_{60}	0.220 mm	0.260 mm
D_{10}	0.085 mm	0.120 mm
Unif. Coeff.	2.58[b]	2.16

[a]20 mi west of Edmonton. [b]Data from Pennell (25).

1. Mixing time of 150 sec for MC 3 mixes, 60 sec for hot mixes, 75 sec for foamed asphalt mixes of Phase 1, 120 sec for foamed asphalt mixes of Phase 2, and 105 sec for sand-emulsion mixtures of Phase 2;
2. Compactive effort constant to simulate standard Proctor density;
3. No drying back or aerating before compaction;
4. Compaction at room temperature;
5. Specimen size of 2 in. diameter by 4 in. long;
6. Curing period of 7 days at 100 F;
7. Immersion period of 14 days at room temperature after 7 days curing; and
8. Triaxial testing at constant lateral pressure, using 9 specimens, each tested at different lateral pressure ranging from 0 to 80 psi, and strain rate of 0.01 in./min.

RESULTS

Since this investigation was concerned with evaluating strength relationships of a fundamental nature, the discussion of results will primarily consider variations in cohesion and angle of internal friction. However, the significance and meaning of test results to practical field conditions can in some cases be implied or stated, as the long range objective of any investigation of this sort lies in its eventual application to the practical problem.

A complete tabular summary of results is given in Tables 3 and 4. The method used to calculate the best-fit Mohr envelope was that introduced by Balmer (1), which has been programmed for solution for the IBM 1620 digital computer (14).

Strength of Cutback Asphalt-Stabilized Sand

Comparison of the data in Table 3, Series B, indicates that within the range of cutback asphalt contents used (3 to 7 percent MC 3) there was essentially very little difference in shearing strength of the compacted cured samples. The addition of cutback asphalt to this particular sand seemed to lower the angle of internal friction only very slightly but did give the stabilized mixture some cohesion. Also, from these cured specimens, it appears that strength properties were not too sensitive to asphalt content, within the ranges used.

TABLE 2

GRADATION OF AIR-DRIED SANDS[a]

Pass No.	Recombined Calculated Gradations									
	Mix No.									
	8	9	10	11	12	13	17	18	19	3
30	100	100	100	100	100	100	100	100	100	100
50	87.0	85.7	83.7	82.5	81.5	87.4	85.7	82.5	87.4	87.0
100	45.0	39.7	30.5	26.2	21.5	7.5	39.7	26.2	7.5	15.5
200	20.2	14.5	12.3	9.4	7.2	2.7	14.5	9.4	2.7	5.7
Unif. Coeff.	4.30	4.02	3.19	2.59	2.44	1.90	4.02	2.59	1.90	2.16

[a]Data from White (29).

TABLE 3

SUMMARY OF TEST RESULTS, PHASE 1

Test Series	Variable	C psi	Ø Deg.	Ave. Tot. Dry Unit Wt., pcf, After Comp.	Cure	Soak	Deg. of Sat., %, After Comp.	Cure	Soak	Remarks
A-1	Control Test	2.5	36.0	100.8						Pure sand series
B-1	7% MC3	8.4	36.0	106.4	106.4		50.7	4.9		
B-2	6% MC3	14.4	35.5	105.8	105.8		55.6	3.4		
B-3	5% MC3	15.5	34.6	104.8	104.8		56.2	3.7		Cured Series
B-4	4% MC3	15.0	34.0	102.8	102.8		58.8	2.8		
B-5	3% MC3	10.6	35.2	100.2	100.2		37.5	3.1		
C-1	5.5% 150-200	3.0	32.6	98.6						
C-2	4.2% 150-200	5.1	32.3	97.7						Hot-mix series
C-3	2.3% 150-200	3.3	32.4	95.6						
D-1	1/2 Std Proc.	9.6	28.5	94.0						Hot-mix Series
D-2	2 Std Proc.	8.4	33.5	98.4						With 4.2% 150-200
D-3	8 Std Proc.	11.8	36.6	102.3						
E-1	8.0% F. Asph.	48.6	32.0	108.0	108.0		90.0	2.4		
E-2	5.5% F. Asph.	52.3	31.7	106.1	106.1		80.0	3.1		Cured Foamed
E-3	4.2% F. Asph.	66.5	30.2	105.0	105.0		74.7	1.4		Asphalt Series
E-4	2.3% F. Asph.	59.8	32.6	102.5	102.5		65.2	2.4		
F-1	8.0% F. Asph.	7.9	33.3	109.3	109.3	108.0	91.8	4.0	37.9	
F-2	5.5% F. Asph.	6.9	32.0	106.1	106.1	105.3	80.5	3.6	43.9	Soaked Foamed
F-3	4.2% F. Asph.	5.6	33.4	105.4	105.4	103.2	76.1	1.0	39.4	Asphalt Series
F-4	2.3% F. Asph.	5.1	32.0	102.4	102.4	98.9	66.1	3.3	43.3	
-1	Process	10.0	32.8	99.5	99.5		62.4	1.5		Cured "Wet" Hot-Mix
H-1	Process	5.2	29.5	99.5	99.5	98.5	62.4	1.5	31.1	Soaked "Wet" Hot-Mix
I-1	11% Water	44.4	33.5	104.7	104.7		49.3	1.6		Cured Foamed Asph.
I-2	7% Water	40.9	34.9	104.1	104.1		36.5	2.4		Series With 4.2%
I-3	3% Water	13.0	34.8	98.1	98.1		18.7	4.9		Asph.
J-1	11% Water	5.8	32.0	104.7	104.7	103.5	49.3	1.6	42.7	Soaked Foamed Asph.
J-2	7% Water	5.9	31.1	104.1	104.1	102.4	36.5	2.4	44.6	Series With 4.2%
J-3	3% Water	0	25.0	98.1	98.1	94.8	18.7	4.9	66.9	Asph.
K-1	10% Volatiles	16.3	35.5	103.9	103.9		33.8	4.4		Cured Aerated Series
K-2	7% Volatiles	12.1	34.4	100.7	100.7		18.0	3.6		With 5% MC3
K-3	4% Volatiles	8.9	31.5	95.4	95.4		4.4	2.4		
K-4	Control Test	3.8	32.8	99.3	99.3		7.8	3.3		Cured Series With Air Dry Sand and 5% MC3

Strength of similar 14-day immersed specimens were shown (25) to have undergone a considerable loss in cohesive strength, with values down to about 2 to 3 psi.

Data given in Table 3, Series K, indicate that aeration of sand-asphalt mixtures before compaction to provide high initial stability had relatively little effect on final strength properties with evaporation of up to nearly 50 percent of the volatiles. However, subsequent aeration resulted in a much lowered final strength, which, although only representing a very limited range of conditions, agrees qualitatively with the work of Herrin (15).

TABLE 4

SUMMARY OF TEST RESULTS, PHASE 1

Test Series	Mix No.	Variable	C psi	Ø Deg.	Ave. Tot Dry Unit Wt., pcf, After Comp.	Cure	Soak	% Asph	Remarks
1-A	1	3% Water	12.0	31.0	98.3	98.3		4.2	Series 1-A run to determine effect of
	2	7% Water	19.9	29.4	98.8	98.8		4.2	mixing or molding water content on
	3	11% Water	25.2	28.1	99.8	99.8		4.2	McGinn pit sand stabilized with 4.2
	4	15% Water	31.2	28.6	103.2	103.2		4.2	percent foamed asphalt; cured.
1-A	2	7% Water	0.0	30.1	98.8	98.8	98.0	4.2	Series run to determine effect of
	3	11% Water	5.0	29.1	99.8	99.8	98.4	4.2	immersion on shear strengths.
1-B	3	Jet Setting	25.2	28.1	99.8	99.8		4.2	Cured. Molding water content 11%.
	5	Jet Setting	29.4	27.7	100.6	100.6		4.2	Run to determine effect of steam
	6	Jet Setting	27.9	29.0	101.4	101.4		4.2	jet setting.
1-B	3	Varying	5.0	29.1	99.8	99.8	98.4	4.2	Molding water 11%. Cured-soaked.
	3	periods of	25.2	28.1	99.8	99.8	98.4	4.2	Cured.
	3	curing and	22.3	29.7	99.8	99.8	98.4	4.2	Cured-soaked-cured.
	6	soaking	22.1	31.7	101.4	101.4	100.3	4.2	Cured-soaked-cured-soaked-cured.
1-C	7	Pugmill	41.7	34.0	103.7	103.7		4.2	Cured.
2-A	8	Gradation	28.7	26.4	108.8	108.8		13.5	Cured. Gradation compared at an
	9	Gradation	23.5	29.0	108.0	108.0		12.0	estimated film thickness of 5.4
	10	Gradation	21.6	28.0	105.5	105.5		10.9	microns.
	11	Gradation	23.5	26.0	102.8	102.8		9.9	
	12	Gradation	27.1	25.3	102.4	102.4		9.2	
	13	Gradation	17.2	25.7	97.6	97.6		7.6	
2-B	17	Gradation	43.0	27.3	102.1	102.1		6.0	Cured. Gradation compared at an
	18	Gradation	30.5	30.8	101.0	101.0		5.0	estimated film thickness of 2.7
	19	Gradation	21.5	28.9	96.3	96.3		3.8	microns.
3-A	14	3% Water	7.7	28.8	97.4	97.4		4.2	McGinn pit sand stabilized with 4.2
	15	5% Water	10.8	30.7	99.4	99.4		4.2	percent residual emulsion asphalt
	16	8% Water	11.9	30.6	100.0	100.0		4.2	content. Cured.
3-A	14	3% Water	0.8	29.1	97.4	97.4	96.7	4.2	McGinn pit sand stabilized with 4.2
	15	5% Water	1.4	29.0	99.4	99.4	97.5	4.2	percent residual emulsion asphalt
	16	8% Water	2.1	29.5	100.0	100.0	99.2	4.2	content. Soaked.

Strength of Hot-Mix Sand-Asphalt

From a practical viewpoint, hot-mix stabilization of sands is seldom practiced; however, the laboratory work in this area was considered desirable as another basis for strength comparisons. The actual process appeared to work very well to distribute the asphalt, but the resultant strength values (Table 3, Series C) were quite low. Since the densities were considerably lower than those of specimens stabilized by other processes, it was decided to vary the density by altering the compactive effort at one particular asphalt content. These results are given in Table 3, Series D, and indicate generally that cohesion was not markedly increased, but the friction angle definitely increased with increased density. Thus, one may reasonably conclude that the low shearing strengths of the hot-mix specimens resulted primarily from low densities.

Strength of Foamed Asphalt-Stabilized Sand

The cohesive strengths for cured samples (Table 3, Series E) ranged from 59.8 psi at 2.3 percent asphalt to a high of 66.5 psi at 4.2 percent asphalt and then to 52.3 psi at 5.5 percent asphalt and 48.6 psi at 8.0 percent asphalt. Friction angle values varied from 30.2 to 32.6 degrees with no apparent relation to asphalt content. These very high shearing strength values were drastically lowered when the same specimens were tested after 14-day immersion, as indicated in Series F. Again, this would suggest a loss of apparent cohesion due to immersion.

Series I shows the effects of variable molding water content on foamed asphalt mixtures at a constant asphalt content of 4.2 percent. It is apparent that the high water content of 15 percent resulted in the highest shearing strength, with a loss of cohesion of cured samples from 66.5 to 44.4 psi using molding water contents of 15 and 11 percent, respectively. A further decrease to 7 percent molding water resulted in 40.9-psi cohesion, which decreased to 13.0 psi with 3.0 percent molding water. Visually, the degree of asphalt distribution seemed no different for 7 percent than for 15 percent molding water; however, at 3 percent water, asphalt distribution was very poor. This would suggest that for a practical application, considering curing difficulties, it may be more advisable to use as low a water content as possible for good distribution of asphalt, even though final strengths would probably be higher with higher molding water contents. This suggestion is supported by the wet and mushy appearance of mixtures at 15 percent water, an observation that would in itself immediately suggest practical construction difficulties.

The soaked strengths of the variable molding water content specimens, as indicated in Series J, were considerably lower than the cured strengths and compared roughly with the soaked strength of the variable asphalt content series. About half the samples with only 3 percent molding water disintegrated after soaking and the remaining ones were badly deformed; the prime reason probably was the poor distribution of binder.

Strength of Wet Hot-Mix Sand-Asphalt

This rather unusual series was run primarily in an attempt to understand or explain the very high cured strengths of the foamed asphalt specimens. A conventional hot-mix, after having cooled, was mixed with 15 percent water, compacted and cured. This was intended to stimulate the foamed asphalt process by coating particles with asphalt and then compacting the cold mass at the same water content as the foamed asphalt mixtures. It was hoped thereby to determine what portion of the high cohesive strengths of the foamed asphalt mixtures was due to apparent cohesion from drying out of the water. It may be noted that at the time this particular series was decided on, insufficient appreciation was given to the fact that the particles would receive their asphalt coatings in quite dissimilar manners in the two processes and that particle to particle uniformity and distribution of asphalt could differ markedly, although visually total distribution of binder was very good in all the hot mixes.

As indicated in Table 3, Series G and H, the unit cohesion was 10.0 psi for the cured series and 5.2 psi for the soaked series, both values being relatively low, although the 5.2 psi is similar to values for soaked values of any other process.

Strength of Foamed Asphalt-Stabilized Sand with Gradation Variations

As indicated in Table 1, there was a slight variation in gradation of Phase 2 sand as compared to Phase 1 sand, even though the source was the same. Results given in Table 4, Series 1-A were considerably lower than those in Table 3, Series E and I, discussed previously. Some concern was felt that the different pug mill and foaming apparatus used in Phase 2 were not performing satisfactorily because of a new method of placing the asphalt under pressure. Since it was known that the alterations in the nozzle jet setting would produce different types of foamed asphalt, Series 1-B was run. Results indicated slight but not significant differences in strength envelopes.

Using Phase 1 sand, results shown in Table 4, Series 1-C, giving a cohesive strength of 41.7 psi and a friction angle of 34.0 degrees, when compared with Table 3,

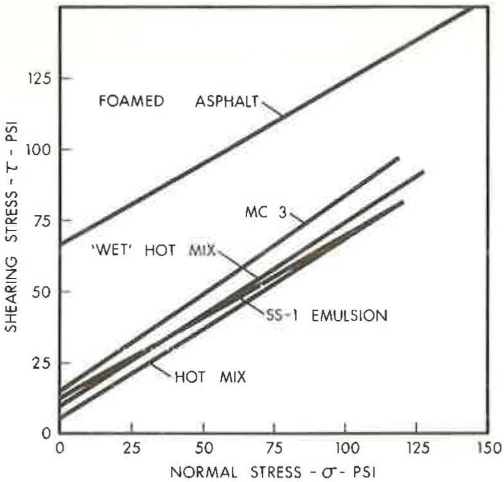

Figure 1. Strength envelopes for specimens cured 7 days at 100 F.

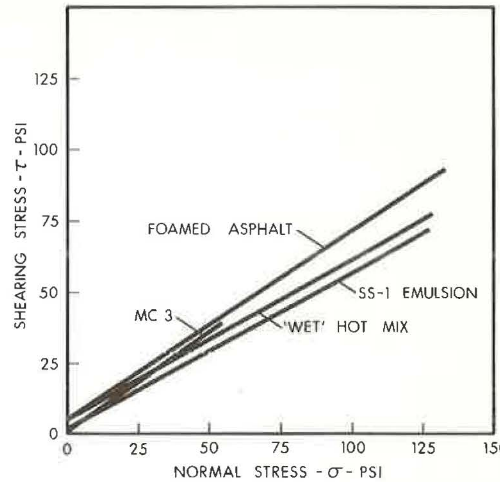

Figure 2. Strength envelopes for specimens cured 7 days at 100 F, then soaked 14 days at room temperature.

Series I-1, gave corresponding values of 44.4 psi and 33.5 degrees, respectively. Thus, it was concluded that the lower strengths obtained in Phase 2 were due to variations in gradation.

To investigate further the effect of varying gradations, several mixes were prepared artificially by reblending finer portions of the original sand that had been removed by dry sieving. Calculated recombined gradations are given in Table 2, with amounts passing the No. 200 sieve ranging from 20.2 to 2.7 percent and corresponding uniformity coefficients of 4.30 and 1.90. The percentages of asphalt required to produce equal film thicknesses for varying gradations were calculated, using surface area constants. Using this method, a film thickness of 2.7 microns corresponded to the optimum asphalt content of 4.2 percent for Phase 1 sand.

Results given in Table 4 for Series 2-A and 2-B indicate that the friction angle was relatively insensitive to changes in gradation, but that the cohesive strength was reduced as the amount passing the No. 200 sieve (filler) decreased. It is thought that much of this variation can be attributed to differing viscosities of the filler-asphalt binder. Similar trends are reported by Kallas et al. (20).

Strength of Emulsified Asphalt-Stabilized Sand

The effect of drying back from a mixing water content of 15 percent, using an SS-1 emulsified asphalt to yield a residual asphalt content of 4.2 percent, is shown in Table 4, Series 3-A. The cured cohesive strengths for the 8.0 and 5.0 percent molding water contents are the same within experimental error, but the 3.0 percent molding water content produced a lower value. This is probably due to the lower density. There is no significant difference in the soaked values.

Strength Comparison

Figure 1 shows Mohr strength envelopes for cured specimens of the various processes at optimum asphalt content. The considerably higher strengths produced by the foamed asphalt process, as well as the similar lower strengths of the other processes, are immediately evident. Figure 2 shows the strength envelopes for the soaked specimens. There is a marked reduction in strength of the foamed asphalt mixes of the same order as of the other mixes.

In view of these results, it would appear that the high strengths of the cured foamed asphalt specimens are due primarily to apparent cohesion arising from capillary forces in the water and asphalt phases. This high apparent cohesion is considered to be due

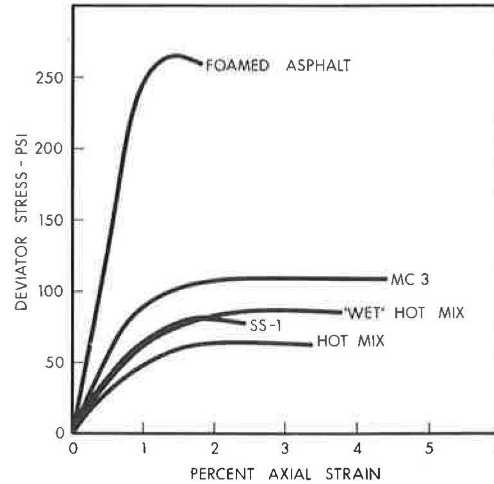

Figure 3. Stress-strain curves for cured specimens.

to the uniform film coverage and void channels of small radii attained in the foamed asphalt mixes.

Although soaking drastically reduces the strength of the foamed asphalt mixes, results given in Table 4 for Series 1-B indicate that the initial high strength is recoverable on recuring. Figure 3 shows typical stress-strain curves for various cured specimens at 20-psi confining pressure. Again the different characteristics of the foamed asphalt as compared to the other mixes is discernible.

Microscopic Examinations of Sand-Asphalt Mixtures

A rather crude, qualitative microscopic examination of the various sand-asphalt mixtures revealed some very interesting differences. These observations were from a fairly limited number of compacted and cured samples but they did reveal that, at least for the materials used in this investigation, the foamed asphalt process resulted in a much more uniform asphalt film thickness around the sand particles than did the other processes. Also, the foamed asphalt process seemed more efficient in orienting the finer particles into the void spaces between the larger particles than the other processes which resulted in a random attachment of fines to the outside of the larger particles. All processes, except the foamed asphalt process, resulted in roughly half the particles having a very thin, practically transluscent film of asphalt. To the naked eye, distribution of asphalt was approximately the same in all of the mixes. Therefore, the total distribution of asphalt throughout the mix was probably very much the same for all of the sand-asphalt mixtures.

CONCLUSIONS

1. The triaxial shear strength of cured foamed asphalt specimens is higher than strengths of specimens produced using cutback asphalt, emulsified asphalt, and asphalt cement. The development of this high strength is sensitive to mixing water content and gradation. Cured strengths of cutback and emulsified asphalt mixes are much less sensitive to gradation.
2. Soaked triaxial shear strengths of these mixes are very similar and relatively insensitive to variations in gradation.
3. It is postulated that the superior shear strengths of the foamed asphalt mixes are due primarily to tension forces in the water and asphalt phases and to high viscosity of thin asphalt films in contact areas between particles. High apparent cohesion may also be attributed to uniformity of films, which in turn causes small uniform void channels of small radii.

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