Stabilization of Sands by Asphalt Emulsion

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This laboratory study investigates whether sands and sand-clay aggregates are amenable to stabilization by asphalt emulsion. Marshall tests were used to evaluate the stability of emulsion-treated sand. Microscopic examination of the treated aggregates revealed the nature and extent of bitumen coating and spreading characteristics of bitumen binder. The results show that well-graded sands with sufficient silt-clay material respond well to emulsions. Portland cement in trace quantities is required, however, to improve the water susceptibility of the mixtures. Because of its superior bonding to siliceous aggregate and its rapid setting tendencies, cationic emulsion is preferred in sand stabilization. Recommendations concerning mixing and compaction moistures are presented. This paper shows that either too little or too much mixing time will result in less than optimum coating. A hypothesis concerning the mechanism of emulsion bonding to aggregates—dry as well as prewet—is proposed.

Bitumen, the most widely used binder for road surfacings, does not carry an electrical charge; its adhesion to aggregates is, therefore, predominately mechanical. Because asphalt emulsions are designed to carry an electrical charge (positive or negative), they are preferentially absorbed by aggregates of opposite charge, which establishes an electrochemical bond.

Early bituminous emulsion contained anionic emulsifying agents such as iron oleate and could only be used with dry aggregates and in good weather. The unreliability of the weather led to the development of the cationic emulsions. Their development was based on the concept that the positively charged surface of the minute globules of asphalt would be strongly attracted to the surface of electronegative asphalt.

Asphalt treatment of sands or aggregates with asphalt emulsions offers several advantages over hot-mixed asphalt treatment. The most important advantage is that mixing can be done at ambient temperatures either in place or in portable plant mixers, which allows the use of low-cost aggregate with a considerable saving in petroleum products. According to the U.S. Bureau of Mines, the total amount of energy-producing petroleum products used in the road-building industry reached a staggering 5 174 000 m^3 (1.367 billion gal) in 1973.

One shortcoming of emulsion-treated mixes (ETM), however, is that strength development is limited by the rate of water loss in the structure. Ultimate cure condition may be achieved by 120 days of curing.

Because emulsified asphalt has been used on a limited scale only, insufficient data are available on the response of emulsion to various aggregates; for this reason, select aggregates have, for the most part, been used in roads during the last 2 decades. For instance, of the 30 projects that Finn and others (7) surveyed in seven states, only seven of the bases included sandy or fine-grained soils. Kerston and Pederson and Korfhage (10, 11) reported poor performance with SS-1 in Minnesota loess and a poor-quality aggregate. Scrimsher and others (16) reported that two cold asphalt emulsion mixtures—one dense graded and the other open graded—placed as 25-mm (1-in) overlays on an existing pavement showed noticeable raveling and the surface developed a rough ride. Recently, Meier (13) reported three projects in the Northwest where fine sand was stabilized with slow-setting grade emulsified asphalt. Again, the performance of two of the three projects was less than satisfactory. One problem encountered involved the difficulty in aerating the mixture, a circumstance that was attributed to the finer gradation. Nevertheless, successful use of emulsified asphalt in sand and cohesive graded sands has been reported (3, 8, 12). As Bratt (2) remarked, however, numerous problems exist, for example, finding a specification that guarantees consistent behavior of emulsions. The numerous failures reported in the literature suggest the lack of a system for evaluating the amenability of a soil to stabilization with asphalt emulsion. To evaluate this problem, facts were sought regarding the following areas:

1. Desired characteristics of aggregate,
2. Type of emulsion best suited for sandy materials,
3. Desired moisture for mixing, compaction, or both,
4. Sensitivity of ETM to water action, and
5. Mechanism of emulsion-aggregate bonding.

MATERIALS AND METHODS

Soils

Four sandy soils were selected for study. The percentage of fines (which refers to the amount of material passing the No. 200 sieve) of these soils varies widely—5, 10, 17, and 20 percent—as does the uniformity coefficient. Soil K37 (Unified Soil Classification symbol SP), a rounded sand with 5 percent fines, is from Baxter, Mississippi; K38 (SW-SM) with 10 percent fines, K40 (SM) with 17 percent fines, and K42 (SM) with 20 percent fines come from the sand-clay topping used in the base construction of the Miss-6 bypass at Oxford.

Asphalt

Emulsified asphalts of slow-setting grades CSS1 and SS1 were used. The properties of the asphalts, as furnished by the manufacturer, are given in Table 1.

Specimen Preparation

Air-dried aggregate was moistened with water before mixing with emulsion. The ingredients (aggregate and emulsion) were hand-mixed for a minute, after which they were mixed by machine until the aggregate was evenly coated. To facilitate even coating, excess moisture (2 to 4 percent) was added during mixing and subsequently evaporated by a blower.

Marshall test specimens 64 mm (2.5 in) high and 102 mm (4 in) in diameter were prepared according to ASTM D 1559, except that 75 blows were applied on both sides instead of 50. These specimens were air dried for 7 days at 50 percent relative humidity and 26°C (73°F) before testing at a loading rate of 51 mm/min (2 in/min). The vacuum soaking test developed by Dunning and Turner (5, 14) was adopted here for evaluating the moisture sensitivity of the mixtures. The tentative ASTM testing method (18) was followed to compact the prepared mixture by using the gyratory testing machine (GTM).

RESULTS AND DISCUSSION

Aggregate-Sand

Important properties of aggregate and sand from the standpoint of emulsion stabilization include (a) mineralogical composition or surface chemistry or both, (b) particle shape and surface texture, and (c) gradation.

The popular theory that siliceous aggregates tend to be electronegative and carbonates of calcium, magnesium, or aluminum tend to be positive has been refuted by recent research studies. Sherwood (17) reported that all aggregates he studied had negative surface charges. By determining the zeta potential of 87 naturally occurring aggregates obtained worldwide, the Highway Chemicals Department of Armak (6) reported negative surface charges in all of those aggregates. Of those 87 aggregates, 34 were limestone and dolomite, and the remaining 53 were various siliceous types. In naturally occurring aggregates, therefore, cationic emulsion is preferred over anionic emulsion.

Microscopic studies as well as Marshall stability values of the various sands reveal that sands exhibiting certain properties are unsuitable for emulsion stabilization. Polished or smooth-textured sands from water-transported deposits and poorly graded sands with few fines are unsuitable. K37 is a typical sand having these attributes. The main problem encountered in K37, especially with cationic emulsion, was that either too long a mixing time (more than 1 min of hand mixing) or drying-

back accompanied by gentle mixing resulted in a reduction of coating or stripping (Figure 1b). Lack of sufficient fines in aggregates could be another reason for stripping. To substantiate this point, soil K37 was modified by adding 4 percent by weight of silty clay fines from soil K38. As shown in Figure 1c, the coatability and mixing stability of modified K37 are substantially improved. Similar results have been obtained by Kallas, Puzinauskas, and Kreger (9), who recommended filler material to improve the stability of hot asphalt mixtures.

The use of emulsion in soil stabilization is restricted to fine granular soils, sands, and silty sands low in clay content. The higher the fines content is (clay in particular), the greater will be the difficulty of obtaining sufficient emulsion mixing stability. For example, if the moisture in soil K42 during mixing is less than ideal, the emulsion will ball up; the resulting ETM exhibits only a fraction of the strength that can be attained under ideal conditions. Although in the range of 5 to 20 percent fines the dry stability increases with fines, as indicated by retained strength after soaking (Figure 2), the resistance to moisture attack decreases. One cautionary note is that neither sands with high fines content (> 20 percent by weight) nor those uniformly graded with low fines content (< 8 percent by weight) should be considered for emulsion stabilization.

Emulsion Type: Anionic or Cationic

Because siliceous aggregates (for that matter, most other highway aggregates) are electronegative, cationic emulsion should be preferred over anionic emulsion. The results of a comparative study of cationic and anionic emulsions in several sands and sandy soils are presented below. The cationic mix requires 1 to 2 percent more moisture than its anionic counterpart. The additional moisture is necessary in cationic emulsions to inhibit premature breaking of emulsion and to promote uniform coating.

In a series of tests, Marshall specimens were molded with moisture content 1 percent less in the anionic mixes than in the cationic mixes. The stability values after 7, 14, 21, and 28 days of air curing showed that the dry stability of anionic-sand mixtures exceeded the cationics. Table 2 gives a comparison of the stability values of specimens of both emulsions after 7 and 14 days of air drying with those of specimens after air drying and vacuum soaking. Contrary to what has been observed in air-dried mixtures, the anionic mixtures, upon soaking, became highly sensitive to water attack as indicated by the lower soaked stability values. The explanation for this anomalous result could be that, because cationic emulsion is positively charged, it is electrochemically bonded to the negatively charged sand grains. The bond between the anionics and the sand grains is purely physical and results simply from the drying process. Therefore, the latter mixtures are more susceptible to water attack than the former, in which stripping action is inhibited because of strong bonds.

Insofar as curing is concerned, cationic emulsion performs better than the anionic one. Experimental results, although not reported here, illustrate that cationic emulsions dehydrate and cure at a considerably faster rate than do anionic emulsions. This advantage is important when aggregates containing variable and excessive amounts of moisture must be used.

In summary, in sandy soils cationic emulsions offer many benefits not available with the conventional anionic emulsions and perhaps cutback asphalts. These benefits include faster setting rates, superior stripping resistance, and, more important, greater resistance to the

deleterious effects of moisture. In general, cationic asphalt emulsions adhere well to a wider variety of aggregates of different chemical composition than do anionic emulsions.

Factors Affecting Emulsion Mixing

Moisture Content

A literature review indicates that moisture contents for mixing and compaction are controversial, to say the least. A survey of emulsion usage in the 50 states indicated that an overwhelming majority of the states favored mixing at the Proctor optimum and compacting slightly below the optimum. Only three states and a few other agencies such as the Bureau of Indian Affairs (13) favored moisture above optimum for mixing.

The moisture for compaction is evaluated in accordance with the following tests:

1. Proctor moisture density test (ASTM D 698-66T) using untreated soil;
2. Moisture-density relation using gyratory testing machine with 690-kPa (100-psi) vertical pressure, 104-kPa (15-psi) air roller pressure, and 3-deg gyratory angle [the density resulting from these settings and 12 revolutions in the GTM machine is shown to be similar to that obtained in the field with a steel wheel roller (15)]; and
3. A factorially designed experiment in which the emulsion and water content were simultaneously varied (by plotting the Marshall stability values in an x-y plot of emulsion versus water content, an optimum stability value can be detected and the formulation at which the best properties are found may be derived).

The results are given in Table 3. The Proctor density of untreated soil in all of the soils is lower than the GTM counterpart; the difference tends to decrease with the increase in fines content. If GTM density is obtainable in the field, the use of Proctor density for field control is not justified. The Proctor optimum moisture, however, compares favorably with the liquid content required for optimum GTM density. Had the Marshall stability been the criterion, the liquid content requirements of soils K37, K38, and K40 are 8, 10, and 12 percent respectively, which agrees with the GTM liquid contents. It is recommended that compaction liquid content be equal to the liquid content for optimum density in GTM.

The amount of moisture present during mixing also has a decided influence on the final distribution of emulsified asphalt in the soil. When the percentage of fines exceeds approximately 5, at the moisture content recommended for maximum density emulsion, the cationic type, especially, breaks, causing mixing difficulties. On the other hand, increasing the moisture by 3 percent and prewetting the aggregate or diluting the emulsion with water facilitates mixing and distribution of binder (Figure 3). As expected, those mixes, when compacted after drying-back to the compaction moisture content (as per Table 3), exhibited higher stability values in the dry state as well as after vacuum soaking (Figure 4). In the light of these results, a recommendation is in order that soil and emulsion be mixed at a moisture content 2 to 3 percent above that specified for compaction.

Uniformity of Mixing

Insofar as mixing is concerned, the researcher is faced with a dual problem. First, how well does the selected emulsion coat the given aggregate during mixing operations? Although slow-setting emulsions are used in this investigation, they, especially cationics, failed to mix with the sand aggregates in dry state. The photographs in Figure 3 clearly show that thoroughly moistening a soil before the emulsion is added facilitates mixing. Presented below is a discussion of how prewetting improves the uniformity of mixing. During mixing, the fine fraction of sand, if dry, preferentially absorbs the water from the emulsion, causing premature breaking of the emulsion. Besides, if the capacity of the aggregate surface for absorption is large, the amount of emulsifier transferred may be sufficient to destroy the stability of the emulsion. The fresh bitumen that precipitates, instead of coating the aggregates, tends to ball up. In dry aggregates, break can also be produced by coagulation. In cationic emulsion the colloidal particles carrying charges of the same sign (positive) tend to repel each other. This is one reason that they do not settle. These charged particles in the cationic emulsion, upon mixing with dry sand, attract charged particles of opposite sign (negatively charged finer particles), and the charges on the emulsion particles are neutralized. Many such particles then unite to form a precipitate, a process called coagulation. The instant ball-up of emulsion in dry or sparingly moistened sand may well be a coagulation phenomenon. With anionic emulsion, however, because of similar charges on the adherend and adherent, coagulation will be absent; the bitumen, therefore, spreads more uniformly yet is only weakly absorbed by the aggregate surface.

On the other hand, when emulsion is added to moistened sand, the asphalt droplet establishes a bond with the aggregate through water molecules as shown in Figure 5b. However, because the affinity of the surface active emulsifying agent is stronger than its affinity for water, in time the former will displace water from the aggregate surfaces irreversibly and establish electrochemical bonds. The schematic in Figure 5 shows how the surface active agent links the bitumen binder and the aggregate.

In summary, it may be concluded that moisture content before mixing, percentages of fines, and porosity of the aggregates, in that order, have the greatest influence on the aggregate coating with emulsion.

Having obtained a uniform mix, the researcher is now confronted by the second aspect of the dual problem: how well the asphalt remains coated (or mixing stability) under adverse conditions of mechanical abrasion during mixing or compaction. If, during the process of mixing, the cohesive forces in the asphalt are greater than the adhesive forces at the asphalt-aggregate interface, the mechanical stresses of mixing cause the asphalt phase to assume a minimum surface area and ball up. Stripping of asphalt due to vigorous machine mixing is shown in Figure 1b. Scrimsher and others recommended that the mixing time be limited to 2 to 15 s for open-graded mixtures and 15 to 20 s for dense-graded mixtures. Depending on soil texture, however, it is recommended that laboratory mixing time be 1 to 2 min.

Moisture Susceptibility of Emulsion-Treated Sand

In spite of high air-dry stability, ETM is highly susceptible to water attack, as indicated by the loss in stability after vacuum soaking (Table 2). The water sensitivity of soil-emulsion mixtures was also measured by the loss in tensile strength, as shown by the split tension test after vacuum soaking.

As stated previously, adding moisture to the aggregate before blending with emulsion improves soaked stability

of all the sand-emulsion mixtures. This improvement is due to the fact that uniformity of mixing is enhanced. To further improve the soaked stability of sand-emulsion mixtures, lime and, subsequently, cement were added in trace quantities. So that spreading of the cement would be uniform it was dry mixed with the sand before water and emulsion were added, in that order. Stability values after vacuum soaking (Figure 4) show that cement treatment, 1 to 1½ percent by weight, further improves the water susceptibility of ETM. For example, with 1½ percent cement, K37 retained 77 percent of its stability after soaking. Cement or lime enters into a surface reaction whereby the hydrogen, sodium, potassium, and so forth on the aggregate surfaces are replaced by calcium from

Figure 1. (a) Mix stability of K37 and cationic emulsion hand-mixed for 1 min, (b) asphalts stripped when machine mixed further, and (c) increased mix stability in K37 when 4 percent fines added.
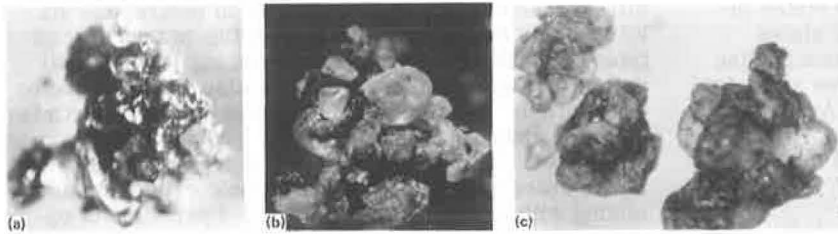

Figure 2. Dry strength, strength after soaking, and moisture absorbed related to percentage of fines.
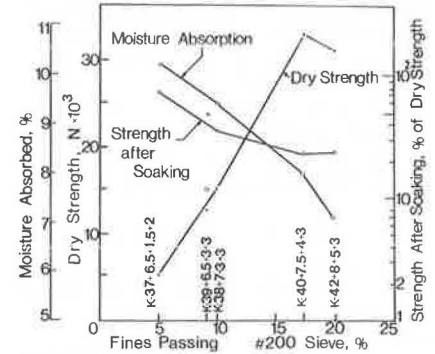
Note: (1 N = 0.225 lbf).

Table 1. Properties of emulsions.

Property	Cationic CSS-1	Anionic SS-1
Emulsion		
Furol viscosity at 28°C	35 to 65	67.7
Settlement, 5 days, percent	—	0.6
Cement mixing, percentage broken	0.1	0.1
Residue (by distillation), percent	64.0 to 68.0	67.7
Base asphalt		
Penetration at 28°C, 100 g, 5 s, cm	149 to 180	146
Solubility in CS_2, percent	—	99.95
Ductility at 28°C, 5 cm/min, cm	100+	40+

Note: 1°C = (1°F - 32)/1.8; 1 g = 0.035 oz; 1 cm = 0.39 in.

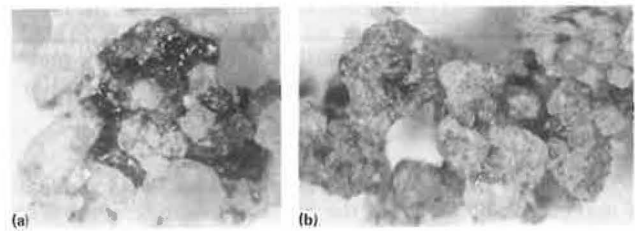Figure 3. Increased mix stability with increasing mixing moisture.

Table 2. Comparison of Marshall stability values of air-dried samples with those of air-dried and vacuum-soaked samples.

Soil No.	Emulsion Type	Percent	Moisture (%)	7-Day Air Cure	7-Day Air Cure and Soak	14-Day Air Cure	14-Day Air Cure and Soak
				Stability (N)			
K37	Cationic	5.5	2.5	4 180	1710	4 335	2200
	Anionic	5.5	1.5	7 070	135	10 430	845
K38	Cationic	7	3	10 365	0	12 455	510
	Anionic	7	2	23 710	380	19 840	735
K40	Cationic	7.5	4	23 350	955	25 330	1335
	Anionic	7.5	3	24 485	710	26 890	510

Note: 1 N = 0.225 lbf.

Figure 4. Marshall stability after vacuum soaking, cationic emulsion.
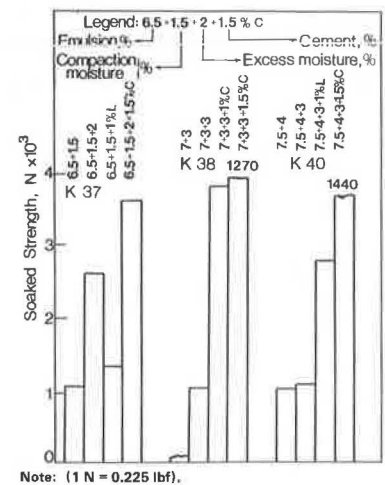

Note: (1 N = 0.225 lbf).

Table 3. Moisture-density relations using various test techniques.

Soil No.	Proctor on Untreated Sand Density (kg/m³)	Proctor on Untreated Sand Moisture Content (%)	GTM Compaction on Treated Sand Density (kg/m³)	Liquid Content (%) Cationic Emulsion	Liquid Content (%) Water	Factorial Exponent Liquid Content (%)
K37	1738.0	10.0	1986.3	6.5	2.0	5.5/2.5
K38	1736.6	12.0	1915.8	7	4.3	7.0/3.0
K40	1906.2	10.0	2050.4	7.5	4.5	7.5/4.5
K42	1949.4	10.7	2037.6	8	4.5	—

Note: 1 kg/m³ = 0.62 lb/ft³.

the cement. The calcium-rich surface formed is shown to react with long chain organic acids to form water-resistant surfaces.

Mechanism of Emulsion Bonding

Asphalt emulsions are intimate mixtures of two immiscible liquids (asphalt and water). An emulsifying chemical, compatible with asphalt and water, has to be added to make the system stable. These chemicals are characterized by having a long hydrophobic (water repelling) hydrocarbon tail and a polar hydrophilic (water attracting) head. As schematically shown in Figure 5a, the hydrophobic tail of the molecule is oriented toward the nonpolar medium, such as asphalt. The surface active molecule acts as a bridge between the two phases, lowering the surface energy and making any transition between the phases less abrupt.

Because cationic emulsions are more favored in stabilization than are anionic emulsions, the following discussion focuses on cationic emulsion and aggregates. When an emulsified asphalt is mixed with an aggregate, the binder is precipitated by the positively charged group of the emulsifier attaching itself to the surface of the aggregate; the surface active agent thus forms a link between the bitumen binder and the aggregate (Figure 5c). Because cationic emulsifying agents carry a positive charge, they adhere to negatively charged aggregates; but in the case of positively charged alkaline surfaces, they are converted into negatively charged areas by the free acid present in the cationic emulsion.

A hypothesis concerning how the emulsified bitumen establishes bond in moistened aggregate was presented earlier and is shown in Figure 5b and 5c.

Another question that remains unanswered is how the stability of ETM increases with age. It has been asserted that in the beginning the bond between the bitumen and the aggregate is partly mechanical and partly electrochemical. Upon curing, however, the moisture content decreases, and the bitumen establishes stronger electrochemical bonds. The strength increase with curing may, therefore, be attributed to added bonds. Second, 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 surfaces of the mineral particles. The microscopic pictures shown in Figure 6 were taken of K40 with 7.5 percent emulsion and 4 percent water after air drying and subsequent drying under

a lamp. The first picture was taken 15 min after mixing, the second one after 3 min of additional drying under a heat lamp. These pictures strongly suggest that, as the water is evaporated from the mixture by moderate heating, the bitumen in the crevices is drawn into coatings on the soil grains by the force of surface tension. The water-resistant films prevent the soil from taking up an amount of water sufficient to cause it to lose stability. Permanent stabilization is thereby accomplished.

CONCLUSIONS

1. Well-graded sands and soils, with fines contents (smaller than 74 μm) between 8 and 20 percent, are amenable to stabilization by emulsion. Uniformly graded sands can be made to perform satisfactorily if blended with silt-sized fines.

2. Because of the superior adhesion property, sands stabilized with cationic emulsion show high early strength and exhibit superior soaked stability. The mixing stability of anionics, however, excels that of cationics.

3. It is recommended that compaction liquid content be equal to the liquid content for optimum density in GTM. Mixing moisture of 2 to 3 percent above that for compaction will ensure adequate mixing stability to give a uniform distribution of binder.

4. The presence of moisture in a soil before the emulsion is added facilitates mixing. Excess silt and clay in a soil adversely affect uniformity of mixing. A reasonable mixing time is necessary to ensure proper coating of the aggregate; too long a mixing time, however, may result in stripping.

5. Portland cement in trace quantities (1 to 2 percent), acting as a stabilizing agent, greatly enhances the soak-stability of sand-emulsion mixtures without the accompanying brittleness of cement-stabilized material.

ACKNOWLEDGMENTS

Figure 5. (a) Asphalt droplets suspended in water. Surface active agent linking (b) bitumen binder and (c) aggregate.
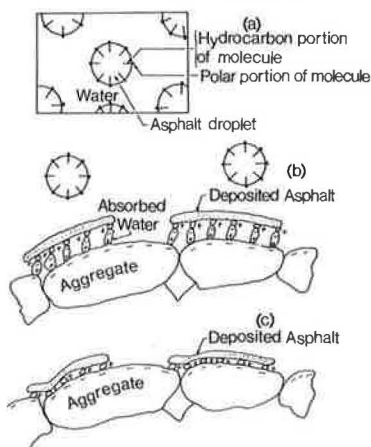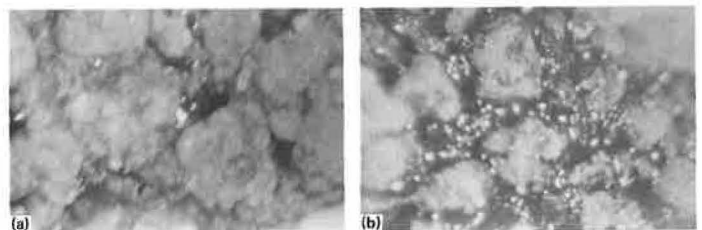

Figure 6. Bitumen spreading due to evaporation and moderate heating after (a) 15 min of air drying and (b) additional 3 min of heat drying.

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