# *Water in Cutback Asphalt Stabilization of Soil*

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The presence of water during the mixing and the compaction phases of asphalt soil stabilization has long been recognized as an important factor. During mixing, water facilitates the even distribution of asphalt throughout the mass. The amount of moisture required for thorough distribution of cutback asphalt apparently increases as the amount of fine material in the soil increases. During the compaction phase the amount of water becomes important mainly because of its effect on density. The amount of moisture required for maximum density of the soil-asphalt mixture is not the same as that for the soil alone.

The desirable moisture contents of a soil-cutback asphalt mixture during mixing and during compaction are major factors that have been investigated. A literature review indicates that these moisture contents are controversial, to say the least. Different concepts of the relation of cutback asphalt content to water content used vary from the belief that 2 percent cutback asphalt replaces 1 percent water, to the belief that cutback asphalt and water have an equivalent lubricating effect on soil grains during compaction.

Various mixtures of soil, cutback asphalt and water were studied. Analysis of the resulting data shows that the percentage of mixing water required to produce maximum strength, maximum standard Proctor density, minimum moisture absorption during immersion, and minimum swelling is different for each property mentioned. However, a compromise moisture content (CMC) for mixing was found at which the variance of the aforementioned properties is a minimum. The CMC was found to be most advantageously determined by minimization using the method of first powers. The CMC was also found to occur very near the mixing moisture content required to produce maximum standard Proctor density of the soil-cutback asphalt-water system.

● SOIL STABILIZATION may be broadly defined as any regulated process that alters or controls soil properties for the purpose of improving the capacity of soil to perform and sustain an intended function. Processes by which soils may be stabilized include the use of other soil or chemical additives or cements, compaction, moisture control, or combinations of these. Asphalt is one of the cements used in soil stabilization for base or subbase courses of pavements.

## TYPES OF ASPHALT

Two types of asphalts, at normal or slightly elevated temperatures, are suitable for mixing with soil; these are the cutbacks and the emulsions. In cutbacks, the viscosity of the asphalt cement is lowered by use of a solvent such as naphtha, kerosene or fuel oil. In the usual emulsions, asphalt cement is reduced to colloidal size droplets and dispersed in water. Use of emulsions with soils is complicated by the fact that clays or fine silts may cause the emulsions to "break" or separate into the constituent asphalt cement and water. This causes mixing difficulties. Excellent results have been reported when the emulsions can be maintained until after mixing. The usual construction procedure is to mix, allow the emulsion to break, and aerate to reduce water in the mix prior to compaction. Usually the emulsion must be designed for the soil used.

At present, cutbacks are the most practical asphalts for soil stabilization. So-called road oils are equivalent to cutbacks made with fuel oil. The road oils are usually prepared as direct residuals from fractional distillation and they are the lowest cost asphalts. Because of their slow-curing characteristics, road oils are not the most suitable for the stabilization of soil mixes; however, they have been used for many years as surface treatments to reduce dust on gravel roads. Road oils can penetrate some soils, and continued annual treatment may build up a satisfactory stabilized mat on a light traffic road after 4 or 5 years. The use of road oil has the disadvantage that roads must be closed to traffic for long periods after treatment.

Medium-curing cutbacks (called MC) and rapid-curing cutbacks (RC) seem to be suitable types of liquid asphalt for soil stabilization. Different grades of cutbacks are designated from 0 to 5, depending on the percent solvent contained. MC-0 and RC-0 each contain about 50 percent solvent, and the percentage decreases to about 18 percent solvent for MC-5 and RC-5. RC cutbacks, in addition to having a more volatile solvent, are made with a harder asphaltic cement, contributing to better binding in the finally compacted and cured mix. The choice between MC and RC depends largely on climate, soil type, and construction practice. Cutbacks cure by an evaporation of volatiles. The higher grades of RC cutbacks may harden before mixing is completed; lower grades contain more solvent and cure more slowly.

The choice of grade of MC or RC also depends on mixing conditions; usually the more solvent and the greater the ease of mixing. Solvents cost about the same as the asphalt and do not directly contribute to strength. The use of high solvent content cutback asphalts may greatly prolong the curing time. For these reasons MC-0 and RC-0 are little used, MC-2 and 3 and RC-2 and 3 represent good compromises. The final choice can be made only after laboratory tests on the soil to be used and after due consideration of climatic conditions. Usually finer-grained soils require a lower viscosity cutback asphalt for mixing.

## MECHANISM OF STABILIZATION

Asphalts are useful for soil stabilization because of their cementing and waterproofing qualities. The cementation property is generally considered to be most effective in providing increased stability in non-cohesive or very slightly cohesive granular soils, such as gravels and sands. The waterproofing property is utilized to greatest advantage in the more cohesive soils or soil-aggregate mixtures. Waterproofing assists in the preservation of the natural stability which these soils have in a dry and well-compacted condition.

Of the theories that have been offered to explain the mechanism of asphalt soil stabilization (4,6,10,14,16), the "intimate mix" and "plug" theories of Endersby (10) seem to have gained widest recognition. Granular materials appear to best fit the "intimate mix" theory that particles are individually coated and stuck together. The theory does not apply to clay materials, where the fine size offers a large surface area to be coated. Also, clays retain a natural cohesion and cannot be separated readily into individual particles. In a fine-grained soil, asphalt tends to coat the soil in small aggregates or clods. The asphalt coats these clods and acts as a waterproofer by plugging voids. This is a modification of the "plug" theory. The plug theory does not appear to apply to purely granular soils.

To summarize the mechanisms: asphalt is mixed with granular soils to coat the grains and act as a waterproofer and binder. In clay-containing soils the clay is a natural binder as long as water is kept out; asphalt is added as a waterproofer for the small clay-cemented agglomerations.

## APPLICATIONS

Asphalt soil stabilization is at present mostly limited to nonplastic and mildly plastic granular soils such as gravels, sands, and soil-aggregate mixtures (3,14,16,18,19,20,24). Economics permitting, granular borrow materials have been added to fine-grained soils to obtain a mixture liable to treatment with asphalt. Successful application of asphalt to fine-grained plastic soils without granular admixtures has been somewhat limited (3,23,25). Recently, laboratory investigations have been conducted on the stabilization of medium-plastic soils with asphalt (5,6,12,14,23,26,27).

## NEED FOR RESEARCH

The use of asphalt as a soil stabilizing agent has been quite extensive and is one of the older soil stabilizing methods. Although this is true, actually less is known about the theory of asphalt soil stabilization than is known about some of the newer methods. Most of the knowledge on the subject has been derived from field experience, which does not allow a close control of variables such as can be maintained in the laboratory. The complexity of asphalt soil stabilization is illustrated in Figure 1 by a listing of the major variables inherent in the subject. It is interesting to note that a detailed study of only one of the contributory factors would require an estimated 8,000 test specimens. The total number of specimens required for a complete analysis and understanding of all possible interdependent variables reaches an astronomical figure of the order of a billion or more. Fortunately the number of samples needed can be reduced considerably by eliminating any study of factors which have very little effect on the final result.

The foregoing statements explain why so many seemingly contradictory statements have been made about asphalt soil stabilization and why a state of mild confusion has resulted. A large part of the confusion appears due to a failure to differentiate the purposes of asphalt in soil; that is, whether it is to function as a waterproofer or as a cement. Further confusion is probably due to a failure to understand the reasons for the presence of water and hydrocarbon volatiles when cutbacks are used.

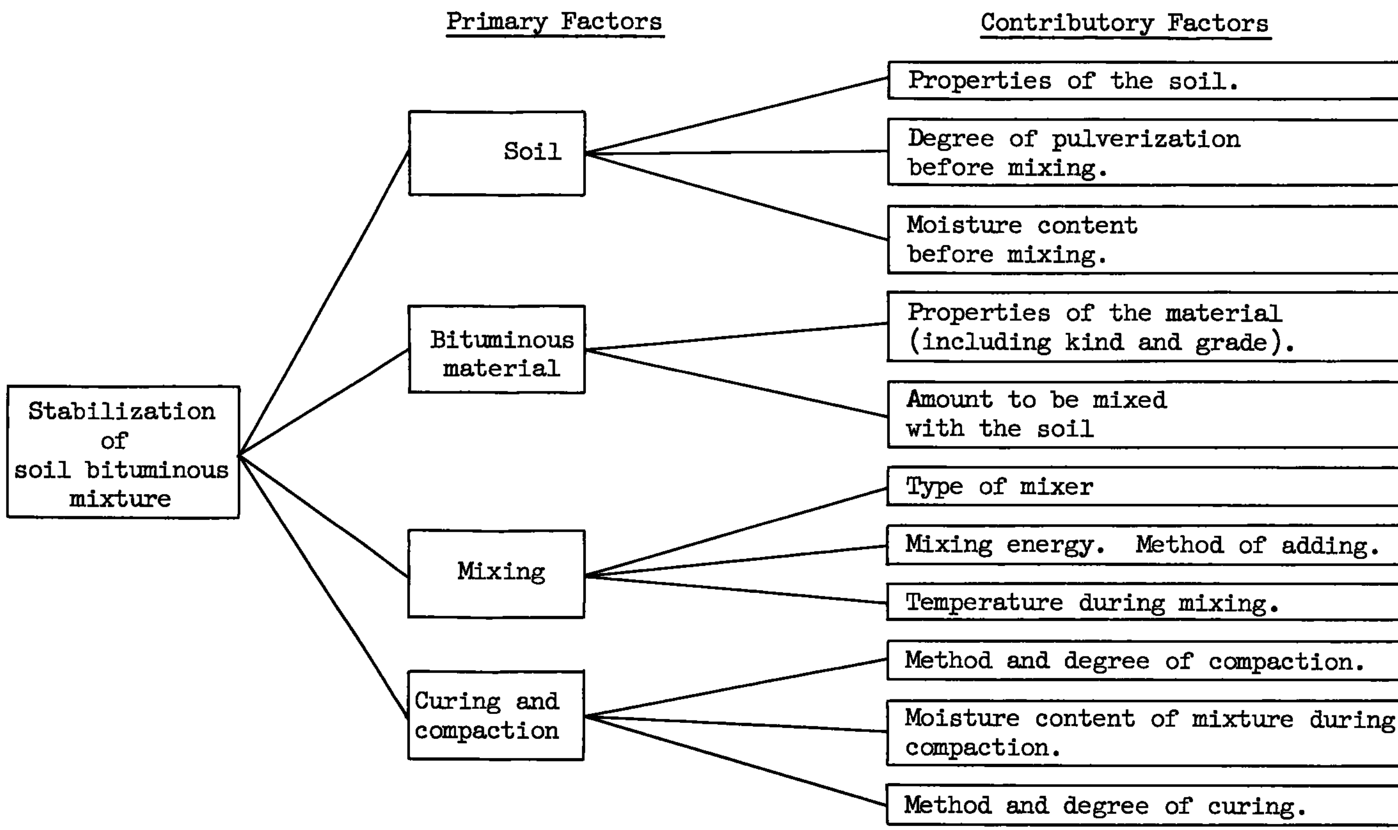



Figure 1. Variables affecting stability of soil-bituminous mixtures.

## ROLE OF WATER

The presence of water during the mixing and compaction phases of asphalt soil stabilization has long been recognized as an important factor. During mixing, water facilitates the even distribution of asphalt throughout the mass as shown by Cape (7). The amount of moisture required for thorough distribution of cutback asphalt apparently increases as the amount of fine material in the soil increases. Asphalt cement can be distributed if the amount of water used is enough to produce a slurry (22). This phenomenon has been used to develop a surface sealing material of soil and asphalt cement (1,8). Hancock (11) has found that the use of wetting agents improves the stability of cutback asphalt treated soils.

During the compaction phase the amount of water becomes important mainly because of its effect on density. Usually a soil-asphalt mixture is the strongest at its maximum density. The amount of moisture required for maximum density of a soil-asphalt mixture is not the same as that for the soil alone.

Although the importance of moisture during these phases of stabilization has been recognized, a satisfactory agreement on the amount of moisture needed has never been reached. A value of moisture content which has been proposed is called the "fluff-point" of the soil (6). The term "fluff-point" may be misleading in that it does not always represent a specific moisture content but may be taken from a range in moisture content. The "fluff-point" is determined by comparison of the density of a number of samples of dry soil to each of which has been added a different amount of water. The moisture and soil are thoroughly mixed and the moisture content of the sample exhibiting the greatest bulkiness or mealiness of texture is called the "fluff-point." The only apparent reason for this choice of moisture content is that there is a maximum void ratio and grain separation when the minimum density occurs. Evidently the logic of this choice was heavily influenced by great faith in the validity of the "plug theory." Further literature study indicates that moisture content is a controversial subject (13). Moisture contents used in mixing asphalt with soil include: optimum moisture for maximum density of the soil, moisture content at the "fluff-point," optimum moisture for maximum density of the soil minus cutback asphalt content and one-half optimum moisture for maximum density of the soil. Different concepts of the relation of cutback asphalt content to water content used vary from the belief that 2 percent cutback asphalt replaces 1 percent water to the belief that cutback asphalt and water have an equivalent lubricating effect on soil grains during compaction.

The effects due to asphalt volatiles during compaction of soil-asphalt mixtures are not clearly understood. Usual practice includes a period of aeration between mixing and compaction of soil-cutback asphalt mixtures with a wide variance in the duration of the aeration. A reduction by aeration of the combined percentage of water and asphalt volatiles varies from one-fifth to one-half of the original content. The asphalt volatile loss is thought to be responsible for an increase in strength of the compacted materials.

## PURPOSE OF INVESTIGATION

The foregoing discussion emphasizes the need of this investigation which, broadly stated, is to study and interpret the effects of water during mixing and during compaction and the effects of asphalt volatiles during compaction on the stabilization of soil with cutback asphalt. A com-

TABLE 1

LOCATION OF SOIL SAMPLES

| Sample No. | County | Section | Tier North | Range | Soil Series | Sampling depth, ft | Horizon |
|---|---|---|---|---|---|---|---|
| 20-2 | Harrison | S-15[a] | 78 | 43-W | Hamburg | 39-40 | C |
| 100-8 | Scott | NW$\frac{1}{4}$, SE$\frac{1}{4}$, S-13 | 77 | 2-E | Fayette | 25-25$\frac{1}{2}$ | C |
| S-6-2 | Benton | NE$\frac{1}{4}$, SE$\frac{1}{4}$, S-16 | 86 | 10-W | Carrington | 3-6 | C |
| 411 | Page | S-27 | 69 | 36-W | Shelby | 3-23 | C |
| 26-1 | Shelby | S-21 | 81 | 40-W | Marshall | 4-5 | C |
| 43$\frac{1}{2}$-1 | Fremont | NW$\frac{1}{4}$, NW$\frac{1}{2}$, S-36 | 69 | 40-W | Marshall | 4$\frac{1}{2}$-5$\frac{1}{2}$ | C |

[a]Sample was obtained behind the third ward school in Missouri Valley.

TABLE 2

PROPERTIES OF SOILS

| Determination | Sample Number | | | | | |
|---|---|---|---|---|---|---|
| | 20-2 | 100-8 | S-6-2 | 411 | 26-1 | 43$\frac{1}{2}$-1 |
| Physical properties | | | | | | |
| L.L., % | 30.8 | 27.1 | N.P. | 41.8 | 39.4 | 51.9 |
| P.L., % | 24.6 | 19.8 | N.P. | 14.9 | 26.9 | 18.5 |
| P.I., % | 6.2 | 7.3 | N.P. | 26.9 | 12.5 | 33.4 |
| C.M.E., % | 19.6 | -- | -- | 21.7 | 19.5 | 28.5 |
| S.L., % | 22.3 | 20.6 | 14.8 | 12.3 | 23.3 | 19.1 |
| Sp. Gr. | 2.71 | 2.72 | 2.68 | 2.67 | 2.71 | 2.72 |
| Lower fluff-point, %[a] | 8 | 5 | 1.5 | 11.0 | 9.0 | 11.5 |
| Std. Proct. density, pcf | 109.9 | | 109.9 | 111.9 | 107.0 | 104.3 |
| Opt. M.C., % | 18.2 | 15.8 | 12.3 | 15.5 | 17.7 | 19.1 |
| Chemical properties | | | | | | |
| Organic matter, % | 0.17 | 0.2 | 0.04 | 0.11 | 0.18 | 0.37 |
| Carbonates, % | 10.17 | 20.0 | -- | -- | -- | 0.5 |
| Cat. Ex. Cap. | 3.8 | 13.4 | -- | 20.0 | 18.2 | 24.4 |
| pH | 8.7 | 7.9 | 6.5 | -- | -- | 6.7 |
| Textural composition, %[b] | | | | | | |
| Sand | 0.4 | 2.8 | 94.4 | 32.7 | 0.9 | 0.4 |
| Silt | 79.8 | 85.2 | 3.4 | 30.8 | 69.7 | 60.2 |
| Clay | 19.8 | 12.0 | 2.2 | 36.5 | 8.1 | 39.4 |
| Colloidal clay | 14.5 | 8.9 | 1.1 | 26.0 | 21.4 | 29.8 |
| Textural classification[c] (B.P.R. system) | Silty loam | Silty loam | Sand | Clay | Silty clay | Silty clay |
| Engineering classification (AASHO) | A-4(8) | A-4(8) | A-3(0) | A-7-6(18) | A-6(9) | A-7-6(18) |

[a]Defined by Benson (12).
[b]Sand - 2.0 to 0.074 mm, silt - 0.074 to 0.005 mm, clay - less than 0.005 mm, colloidal clay - less than 0.001 mm.
[c]Classified texturally by the Bureau of Public Roads System except that sand and silt sizes are separated by the No. 200 sieve.

plete understanding of the effects of these variables on a compacted mix should aid in arriving at a more intelligent and efficient design of soil-cutback asphalt mixtures than exists today.

## MATERIALS

### Soils

Soil samples were chosen from the loess, glacial till and sand materials of Iowa to represent not only widespread soil types but also textural variations of soil in general. Samples 20-2 and 100-8 represent the friable, calcareous loess in western and eastern Iowa, respectively. Sample 20-2 was from the deep loess bordering the Missouri River and 100-8 was from the deep loess along the Mississippi River. A sub-study comparing testing apparatus was made using samples 26-1 and $43\frac{1}{2}$-1 which represent the plastic loess in southwestern Iowa.

Sample S-6-2 is a fine sand from east central Iowa with a low clay content of only 2 percent. This material represents the fluvial fine sand deposits of the area.

Sample 411 is Kansan glacial till from southwestern Iowa. Kansan till is one of the most abundant surficial materials in the southern part of Iowa and may be found in almost all parts of Iowa. The particle size distribution and mineralogy of Kansan till is in general similar in all areas (21).

Sample locations, soil series and physical properties of the soil materials are presented in Tables 1 and 2.

### Asphalt

Cutback asphalts of grades MC-0, MC-2 and MC-4 were used. The properties of the asphalts as furnished by the manufacturer are listed in Table 3. Medium-curing cutback asphalts were selected for the reasons previously given.

## LABORATORY PROCEDURES AND TESTS

Standard tests and laboratory techniques are not always sufficient or applicable procedures for conducting research. This was found to be true in the present investigation, and a number of sub-investigations were necessary to develop suitable methods of test (15).

### Proportioning of Materials

All additions of water and cutback asphalt were calculated as a percentage of the weight of oven-dry soil with which they were mixed. Cutback asphalt percentages represent the total weight of asphalt cement plus hydrocarbon volatiles. In other words 6 percent cutback asphalt means a mixture having a ratio of 6 lb of liquid cutback asphalt to 100 lb of oven-dry soil.

### Moisture and Hydrocarbon Volatile Determinations

Determinations of moisture content in samples devoid of cutback asphalt were made by drying the samples in an oven at 105 to 110 C. Moisture contents of samples containing cutback asphalt were determined by distillation of all volatile material from the sample with a subsequent separation and measurement of the amount of water and hydrocarbon vola-

TABLE 3

PROPERTIES OF CUTBACK ASPHALTS[a]

| Properties | Test Method | Specification Designation | | | |
|---|---|---|---|---|---|
| | | MC-0 | MC-2 | MC-4 | RC-2 |
| Furol viscosity at 77 F, sec | ASTM D 88 | 98 | | | |
| Furol viscosity at 122 F, sec | | | 143 | | |
| Furol viscosity at 140 F, sec | | | | 211 | |
| Furol viscosity at 180 F, sec | | | | | 138 |
| Specific gravity (77/77 F) | AASHO T 43 | 0.939 | | 0.967 | 0.949 |
| Distillation | | | | | |
| Distillate (percent of total distillate to 680 F) | ASTM 402 | | | | |
| To 370 F | | | 2.3 | 0.0 | |
| To 437 F | | 71.4 | 20.9 | 9.5 | 41.7 |
| To 500 F | | | 72.1 | 57.1 | 73 |
| Residue from distillation to 680 F Volume percent by difference | | 65 | 78.5 | 89.5 | 76 |
| Sp. gravity of distillate (77/77 F) | | 0.79 | 0.83 | 0.84 | -- |
| Tests on residue from distillation, pen. 77 F, 100 g, 5 sec | | 1000 | 210 | 215 | 96 |
| Sp. gravity of residue (77/77 F) | ASTM D 71 | 1.005 | 1.015 | 1.005 | 1.012 |
| Solubility in carbon tetrachloride | ASTM D 4 | 99.95 | 99.99 | 99.98 | 99.56 |
| Temperature of use for mixing, deg F | | 50-120 | 100-120 | 175-225 | 80-150 |
| Oliensis spot test | | Neg. | Neg. | Neg. | Neg. |

[a]Properties furnished by the Standard Oil Company of Indiana.

tile material (15). The latter method determines both water content and hydrocarbon volatile content of the sample.

## Mixing of Materials

Test specimens were prepared from batches mixed by a Hobart C-100 kitchen mixer. The required amount of water (varied with experiment performed) and 1,500 grams of soil were first machine-mixed for 2 min. Next the sides of the mixing bowl were scraped and the materials were then mixed for an additional 3 min. The soil-water mixture was then stored in an air-tight container for 16 to 24 hr before the addition of cutback asphalt. The cutback asphalt was heated to the middle of the range of temperatures recommended by the Asphalt Institute and hand mixed into the moist soil to prevent splashing. Next the materials were machine-mixed in the following order: $1\frac{1}{2}$ min of mixing, sides were scraped, $1\frac{1}{2}$ min of mixing, sides again scraped and a final 2 min of mixing (15).

One of the sub-investigations was a study of the amount of hydrocarbon volatile material lost during the process of mixing cutback asphalt with soil. Determination of the loss of hydrocarbon volatiles while mixing 10 percent MC-0 at room temperature with oven-dry soil, and with air-dry soil at room temperature showed that the loss is very small; the loss after 7 min of mixing with oven-dry soil at 110 C and cooling to room temperature in a desiccator was 1.27 percent of the hydrocarbon volatiles and the loss using air-dry soil was 1.21 percent. The smaller loss in the presence of hydroscopic moisture can be explained by considering the mechanism of mass transfer:

Loss of hydrocarbon volatiles through evaporation in a system of this type is essentially a diffusional phenomenon. The system can also be considered to consist of two immiscible liquids, water and kerosene or water and gasoline. Each component liquid exists in a pure state and therefore exerts its normal equilibrium vapor pressure at the existing temperature. The rate of evaporation in either a static or dynamic atmosphere is proportional to the surface exposed multiplied by the difference between the partial pressures of the evaporating component at the interface and in the surrounding atmosphere. Increased water contents do not affect partial pressures and therefore they reduce the amount of hydrocarbon volatile loss by reducing the exposed surface area of the more volatile hydrocarbon material. Because the hydrocarbon volatile loss in the presence of a small amount of water was negligible, the loss with larger amounts of water present will be even less and for practical purposes can be considered negligible.

## Aging Mixtures

Batches of cutback asphalt-soil-water mixtures that were used for studying the amount of water required during mixing, were stored 4 hr in an air-tight container before molding specimens. The purpose of this aging was to insure soil-moisture equilibrium conditions.

## Drying-Back Mixtures

Batches of cutback asphalt-soil-water mixtures that were used for studying the amount of water and hydrocarbon volatile material remaining before molding were air-dried for various periods of time. The cutback asphalt-soil-water mixtures were placed in shallow pans and covered with a layer of gauze and a 1-in. layer of cotton. The coverings reduced the thermal gradients and vapor concentration gradients, which in turn reduce the rate of vapor phase mass transfer from the surface of the drying material. The reduced rate of surface mass transfer causes the liquid and vapor conditions to remain static and fairly close to equilibrium throughout the drying mixture.

## Molding

Following either aging or drying-back, soil-cutback asphalt mixtures were molded into 2-in. diameter by 2-in. high specimens using standard Proctor compactive effort (9). The molds were 5-in.-long brass cylinders having a 2-in. inside diameter. Compacted material in excess of 2 in. was extruded from the cylinder and trimmed. The specimen remained within the cylinder through testing (15).

## Testing Specimens

The stability of specimens was evaluated by the Iowa Bearing Value test immediately following the soaking period. The Iowa Bearing Value test (IBV test) was chosen as a means of stability evaluation for several reasons (15). The IBV test is believed to simulate field conditions more nearly than other tests, it requires one-twentieth the amount of material and less than one-half the time required by the CBR test. The IBV test molds are small and require little space in humidity or storage cabinets.

A singular disadvantage is the fact that the IBV test is limited to medium- and fine-grained soils, although a limited amount of research indicates that materials containing up to 25 percent $\frac{1}{4}$-in. gravel may be tested (9). The soil materials used in this study were medium and fine grained.

The IBV test is a miniature bearing test patterned after the California Bearing Ratio test. The test specimen is compacted into a 2-in. diameter mold and struck off to a height of 2 in. A 5/8-in. penetration rod is forced into the specimen by a testing machine, and the load at various depths of penetration is recorded and graphed. In this investigation the load corresponding to 0.08-in. penetration is called the IBV.

In the IBV test, specimens may be tested in any condition such as soaked, air-dry or after freezing and thawing. In this investigation, specimens in brass cylinders were immersed in distilled water at room temperature with a surcharge (equivalent to that used in the CBR test) and allowed to soak for 7 days before testing. Seven days was chosen as the soaking period because it was found that a maximum loss in stability, as measured by strength, occurs within this period.

The IBV test was developed in the Engineering Experiment Station of the Iowa State College and is being correlated with the CBR test (2,9,17).

## Review of Procedure

A brief step-wise review of the laboratory procedure is presented for the sake of clarity:

1. Proportion soil and water
2. Mix
3. Store 16 to 24 hours
4. Mix by hand
5. Add liquid cutback asphalt
6. Mix by hand
7. Machine mix
8. Age or dry-back
9. Mold
10. Immerse in distilled water
11. Test

# INVESTIGATION

Water contents during mixing and during compaction of soil-cutback asphalt mixtures have marked effects on the properties of the resulting stabilized material. The amount of moisture present during mixing also has a decided influence on the final distribution of cutback asphalt in the soil mass. The main purpose of this investigation was to determine what moisture control should be exercised to insure a stabilized material having an optimum combination of properties. Two processes of cutback asphalt soil stabilization were investigated: in Process I, soil, cutback asphalt and water were mixed and immediately compacted; in Process II, soil, asphalt and water were mixed and the mixture was dried back to some lower moisture content before compaction.

The difference between Process I and Process II was the stage in the process at which the water content was varied. In Process I the water content was varied during mixing and the mixture was compacted with a water content equal to that used in mixing. In Process II the water content during mixing was sufficiently high to insure good cutback asphalt distribution; the water content was then changed from that used during mixing by drying back before compaction.

Process I

The effects of moisture content during mixing on the density, IBV, absorption, expansion and the total 7-day soaked moisture content were studied by testing specimens molded from different batches of soil, asphalt and water in which the water content was varied. All other quantities and qualities such as the amount and type of soil, and the amount and type of cutback asphalt were maintained constant for any one study. Each of the four soils was studied in this manner and compared using admixtures of 6 and 10 percent MC-2 and MC-4 cutback asphalt. The sand sample (S-6-2) was treated with only 3 percent MC-2 because higher percentages of MC-2 cutback asphalt produced mixtures of such a liquid consistency that molding was impossible. The use of MC-4 with the sand permitted treatments of both 3 and 6 percent. Again it is emphasized that water content was the only variable in any singular study of constant cutback asphalt content. The method of analysis can be clarified by an examination of the data presented.

Density was calculated as weight of dry soil per unit volume and is expressed in pounds per cubic foot. IBV was expressed in pounds, absorption was calculated as the amount of moisture gained by a specimen during the 7-day immersion period and was expressed as a percentage of the oven-dry weight of soil contained in the specimen. Expansion of specimens was expressed as a percentage of the original height of the specimen concerned because the specimens were laterally confined and expansion occurred in one dimension only. Total 7-day soaked moisture content was expressed as percentage of the oven-dry weight of soil contained in a specimen.

The data are presented in Figures 2, 3 and 4 as graphs with density, IBV, absorption, expansion and total 7-day soaked moisture content treated as dependent variables. The independent variable is the water content during mixing, expressed as a percentage of the oven-dry weight of the soil in each specimen. Each point on the graphs represents an average of three values.

The curves of IBV, density and of total moisture content after 7 days' soaking all show either a maximum or a minimum where an optimum mixing moisture content exists for each combination of soil and type and amount of cutback asphalt. The optimum moisture contents for the foregoing are seldom coincident.

The absorption and expansion curves are similar in character. Both sets of curves are, in general, a logarithmic type asymptotic to some minimum value. The curves indicate that the best absorption and expansion performances are obtained with the highest mixing water content possible. However, a gain in absorption and expansion performance by increasing the mixing water content is obtained only at the expense of other desirable properties.

Somewhere within the range of moisture studied there is a mixing moisture content which represents the best compromise when all properties are considered. The compromise point was found by graphical analysis of the data, using the method of first powers in which a minimization of the summation of individual property deviations from a datum is calculated. More accurate methods of analysis could be performed by using either the

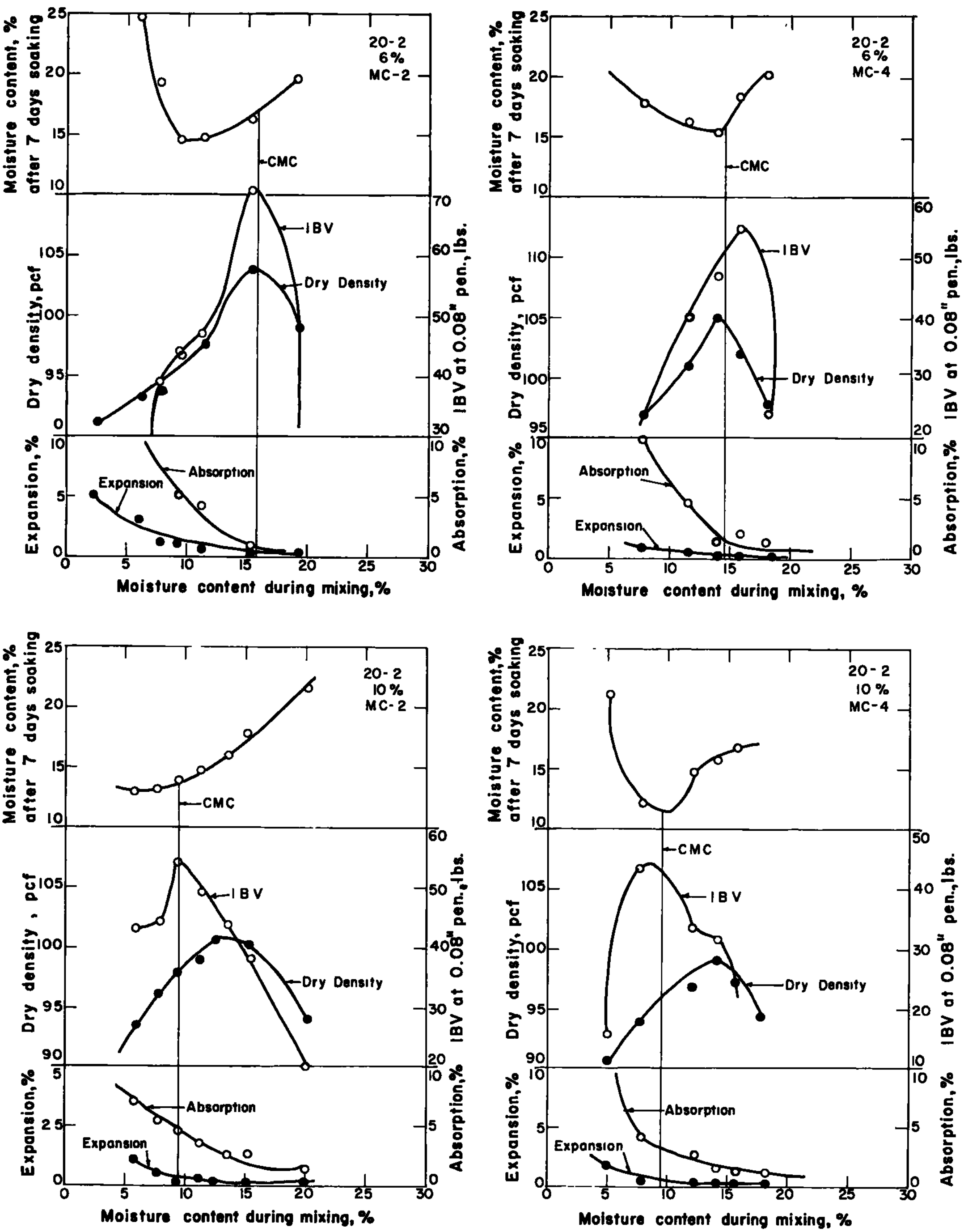



Figure 2. Graphs of moisture content during mixing versus the IBV, dry density, absorption, expansion and total moisture content after 7 days soaking of soil-cutback asphalt compacted specimens. The soil-cutback asphalt compositions are listed on each graph. The amount of residual asphalt cement in 6 and 10 percent MC-2 is 4.93 and 8.2 percent, and in 6 and 10 percent MC-4 is 5.47 and 9.11 percent. The vertical line in the center of the graph indicates the CMC.

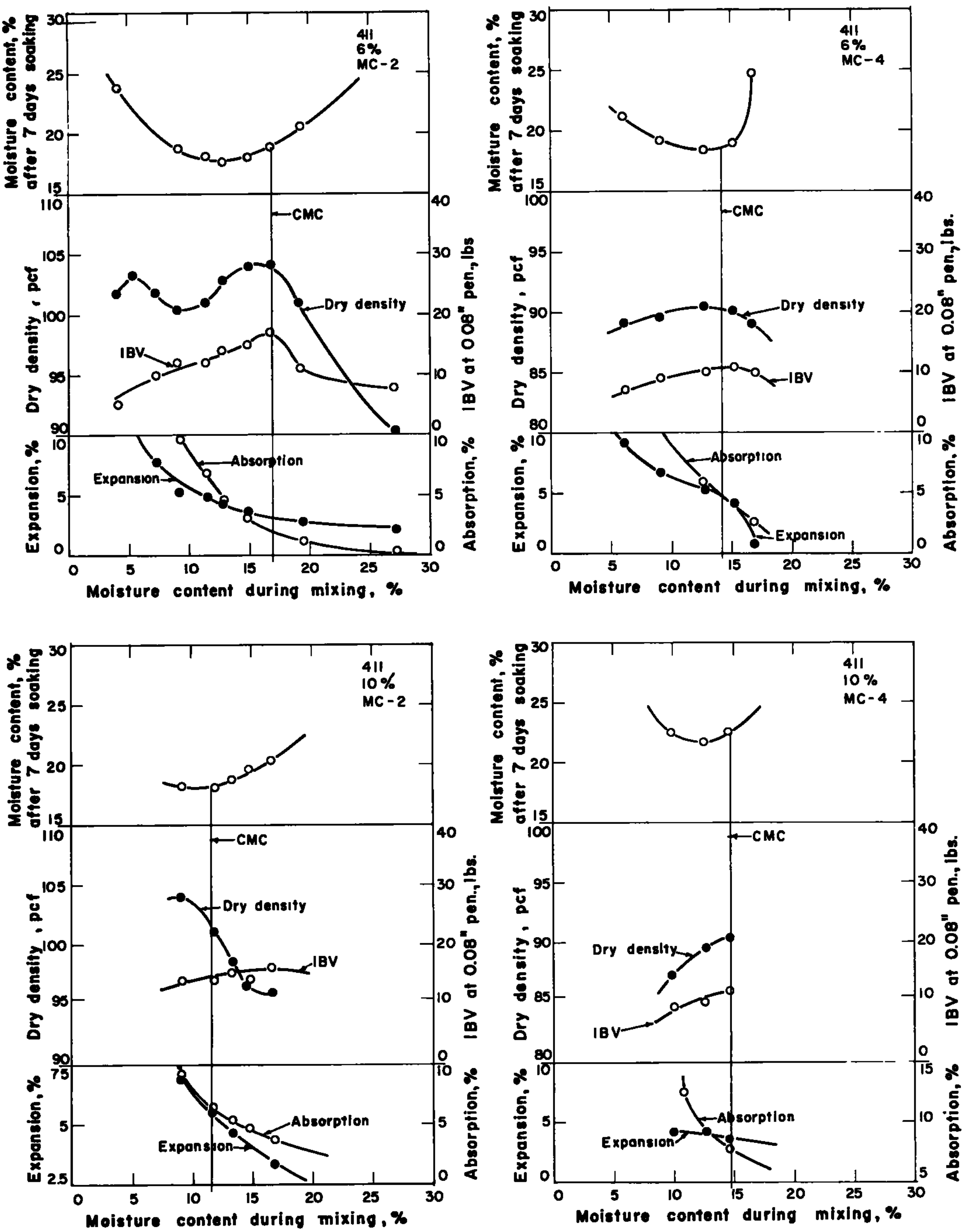



Figure 3. Graphs of moisture content during mixing versus the IBV, dry density, absorption, expansion and total moisture content after 7 days soaking of soil-cutback asphalt compacted specimens. The soil-cutback asphalt compositions are listed on each graph. The amount of residual asphalt in 3, 6 and 10 percent MC-2 is 2.47, 4.93, and 8.2 percent, and in 3 and 6 percent MC-4 is 2.7 and 5.4 percent. The vertical line in the center of the graph indicates the CMC.

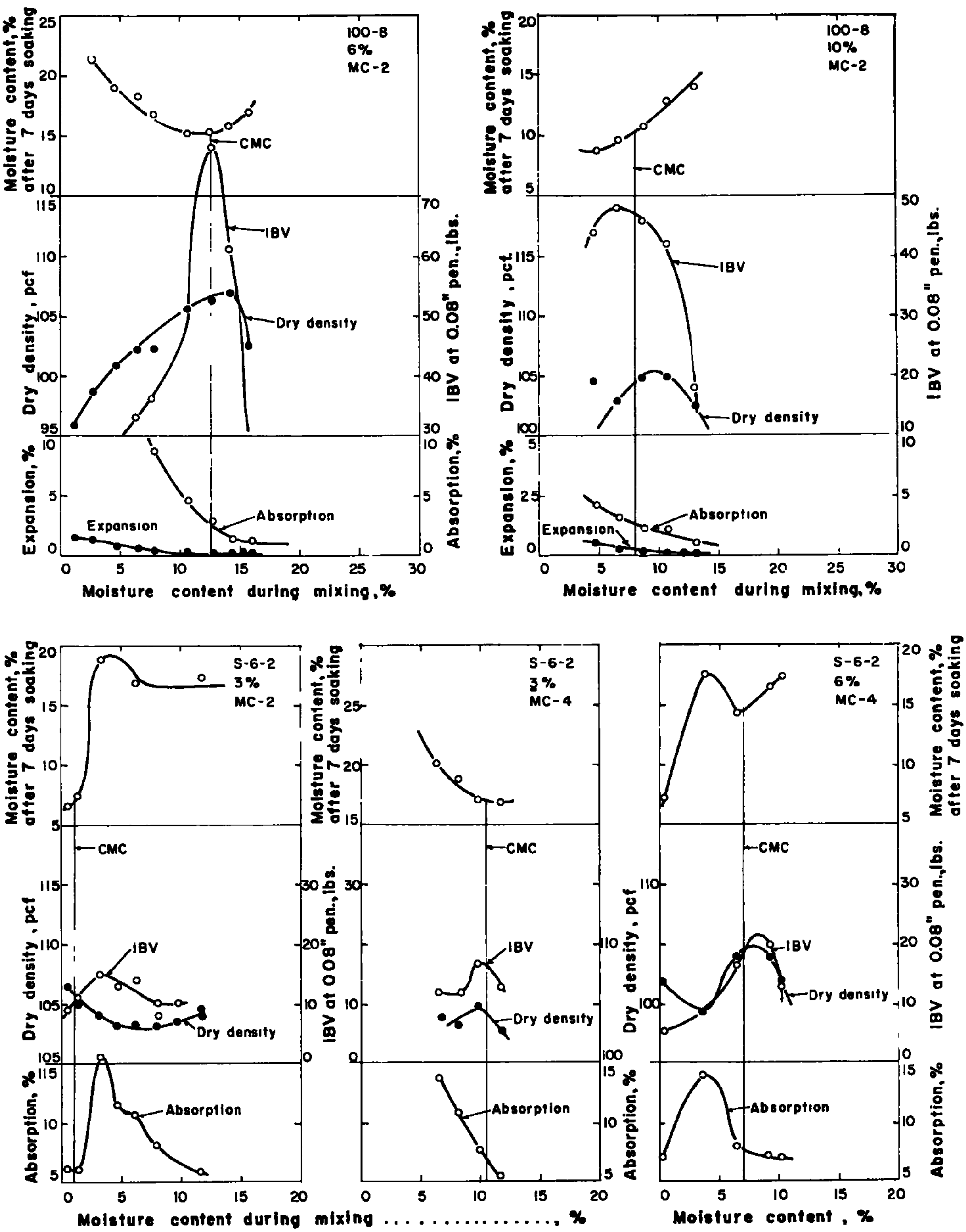



Figure 4. Graphs of moisture content during mixing versus the IBV, dry density, absorption, expansion and total moisture content after 7 days soaking of soil-cutback asphalt compacted specimens. The soil-cutback asphalt compositions are listed on each graph. The amount of residual asphalt cement in 6 and 10 percent MC-2 is 4.93 and 8.2 percent, and in 6 and 10 percent MC-4 is 5.47 and 9.11 percent. The vertical line in the center of the graph indicates the CMC.

method of least squares or the method of least cubes. However, the latter methods are far more complex and require an exact knowledge of the equations of the functions relating the properties in question for accuracy. Curves could be fitted to the numerical data but in so doing, errors of a serious nature are apt to be introduced. Errors of this type offset the increased accuracy of the more complex methods, so the simplest method was used.

Each property exhibits one best value, either a maximum or a minimum, which was used as a datum. The difference between a property value and the datum value was then calculated at each moisture content as a percentage of the datum value. The percentage of deviation of all properties from their respective datums were summed at each mixing moisture content and the summations of deviations were then plotted versus mixing moisture content. The mixing moisture content corresponding to the minimum value of the summation of deviations is then the best compromise moisture content (CMC). The mixing CMC was found by this method for all soils and combinations of cutback asphalt used except for some of the sand mixes in which no definite maximum or minimum were evident. The CMC for the latter were visually estimated.

The data resulting from the tests and calculations are given in Table 4. Optimum moisture for the raw soil is included primarily as a matter of interest. The mixing moisture content corresponding to maximum IBV, maximum density and minimum total moisture content after 7 days' immersion are shown for comparison with the mixing CMC at which the best over-all results are obtained.

TABLE 4

DATA FROM PROCESS I—MIXED AND MOLDED

| Soil | Amount and Type of Cutback Asphalt[a] | Optimum Moisture of Soil, % | Mixing Moisture Content Required to Produce: Maximum IBV | Maximum Dry Density | Minimum Moisture Content After 7 Days Soaking | Calculated MC Where Minimum Summation of Deviations Occurs, CMC, % |
|---|---|---|---|---|---|---|
| 20-2 | 6% MC-2 | 18.0 | 15.5 | 15.7 | 10.1 | 15.8 |
| | 10% | | 9.6 | 13.6 | 7.2 | 9.5 |
| | 6% MC-4 | | 16.0 | 14.0 | 13.8 | 14.5 |
| | 10% | | 8.5 | 13.9 | 10.0 | 9.5 |
| 100-8 | 6% MC-2 | 15.8 | 12.7 | 13.8 | 11.5 | 12.5 |
| | 10% | | 6.6 | 9.6 | 4.5[b] | 8.0[b] |
| 411 | 6% MC-2 | | 16.6 | 15.8 | 12.3 | 16.3 |
| | 10% | | 16.5 | 9.0 | 10.4 | 11.6 |
| | 6% MC-4 | | 14.7 | 12.5 | 13.1 | 14.2 |
| | 10% | | 15.2 | 15.7 | 12.3 | 14.6 |
| S-6-2 | 3% MC-2 | 12.3 | 3.2 | 0.5[b] | 0.5[b] | 1.0[b] |
| | 3% MC-4 | | 10.0 | 9.8 | 11.7 | 10.5 |
| | 6% | | 8.5 | 8.0 | 0.5[b] | 7.0[b] |

[a]Amount of residue in 6% MC-2 cutback asphalt is 4.93%, 10% is 8.2% and in 6% MC-4 5.47% and in 10% MC-4 9.11%.

[b]Visually estimated because maxima and minima were indefinite.

Examination of these data show that the mixing moisture for maximum IBV and for maximum density closely correspond to the mixing CMC. Exact correspondence would produce a straight line graph passing through the origin with a slope of 45 deg in each case. Plots of mixing moisture for maximum IBV and for maximum density versus CMC are shown in Figure 5. Both plots follow a 45-deg line fairly well. The mixing moisture for maximum IBV appears to give the best correlation; however, the mixing moisture for maximum density gives a good correlation.

Absorption or expansion due to soaking cannot be used as criteria for predicting mixing moisture for maximum performance because there is no convenient control point on the curves as shown in Figures 2, 3, and 4. The only possible point of control is the minimum value in each case and the minimum values lie too far to the right of the moisture range in which maximum density, maximum IBV and minimum total moisture content after 7 days' immersion occur. Inclusion of absorption and expansion in the CMC computation would displace the CMC to the right far enough to be out of the moisture range previously mentioned. These properties are determined after specimens have been soaked for one week. The properties are also dependent on the moisture content at the beginning of the soaking period, because the amount of absorption or expansion is partially dependent on the amount of air void space available for the entry of water. The moisture content at the beginning of the soaking period is also variable, so the amount of absorption or expansion is a relative value.

The mixing moisture for the maximum density of the soil asphalt mix is the most practical moisture content for use as a guide in determining water requirements for cutback asphalt soil stabilization.

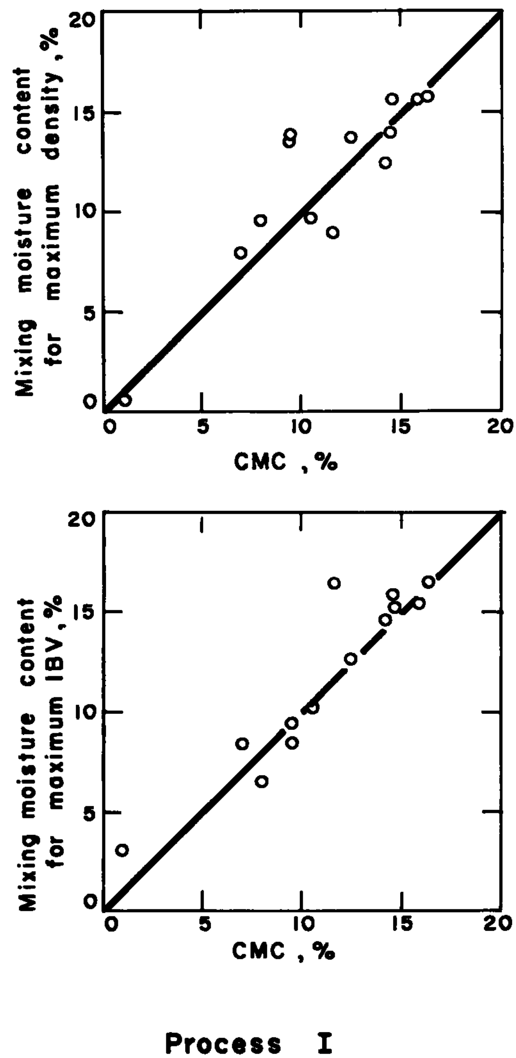



Figure 5. Graphs comparing mixing moisture content for maximum standard Proctor density and mixing moisture content for maximum IBV with the compromise moisture content. Exact correlation of the experimental data would fall on the indicated 45-deg line. This relation holds true for the silty and clayey soils used in this investigation.

The density tests can be run in a relatively short time; the IBV test requires at least a week.

Process II

The effects of moisture content during compaction on the density, IBV, expansion and the total 7-day soaked moisture content were studied by testing specimens molded from different batches of soil, asphalt and water in which the moisture and hydrocarbon volatile content had been changed by drying the material after mixing. All other quantities and qualities such as the amount and type of soil, and the amount and type of asphalt were maintained constant for any one study. Batches were mixed at either the standard Proctor optimum moisture or at the liquid limit of the raw soil and in some cases at the plastic limit. Each soil was studied in this manner and compared to other soils using 6 and 10 percent MC-2 and MC-4 cutback asphalt. The sand sample was again treated as stated in the previous section describing Process I. Property values were calculated and expressed in the same units as before.

The data are presented in Figures 6, 7, 8 and 9 as graphs with density, IBV, expansion and total 7-day soaked moisture content treated as dependent variables. The independent variable is the water content during molding. Each point on the graphs represents an average of three values.

The data are presented in Figures 6, 7, 8 and 9 in the same manner as the data for Process I. The resulting curves are of the same general type as those obtained in Process I and were analyzed as described under Process I.

A close correlation, except for sand, exists between either the moisture contents for maximum density or maximum IBV and the dried back CMC as shown in Figure 10; the results from sand tend to be erratic and the CMC must be estimated by eye. Both plots follow a 45-deg line and the same general statements apply as were discussed under Process I. It is important to note that the dried back moisture content for maximum density of the soil-asphalt mix is the most practical criterion for determining the water requirements of Process II, with the possible exception of sand. The data indicate that for sand the CMC lies on the dry side of the dried back moisture content for standard Proctor density.

Comparison of Processes I and II

Tables 5 and 6 compare Processes I and II on the basis of the values of IBV, density and total 7-day soaked moisture content obtained at the CMC of each process. All property values of specimens resulting from Process I were superior to those of corresponding specimens prepared by Process II with the exception of total 7-day soaked moisture content of the sand specimens mixed with MC-4. It would then appear that Process I produces the best results with the textural types of soil studied.

Heavier clays may require the use of Process II, because the CMC of Process I may lie within the plastic range of the soil. Should this be so, adequate mixing of such a soil with asphalt at the CMC of Process I is impossible. The higher mixing moisture contents employed in Process II become the only possible solution because mixing is easily done near the liquid limit of highly plastic soils. The use of Process II increases the cost, because the addition of the drying back stage may economically limit

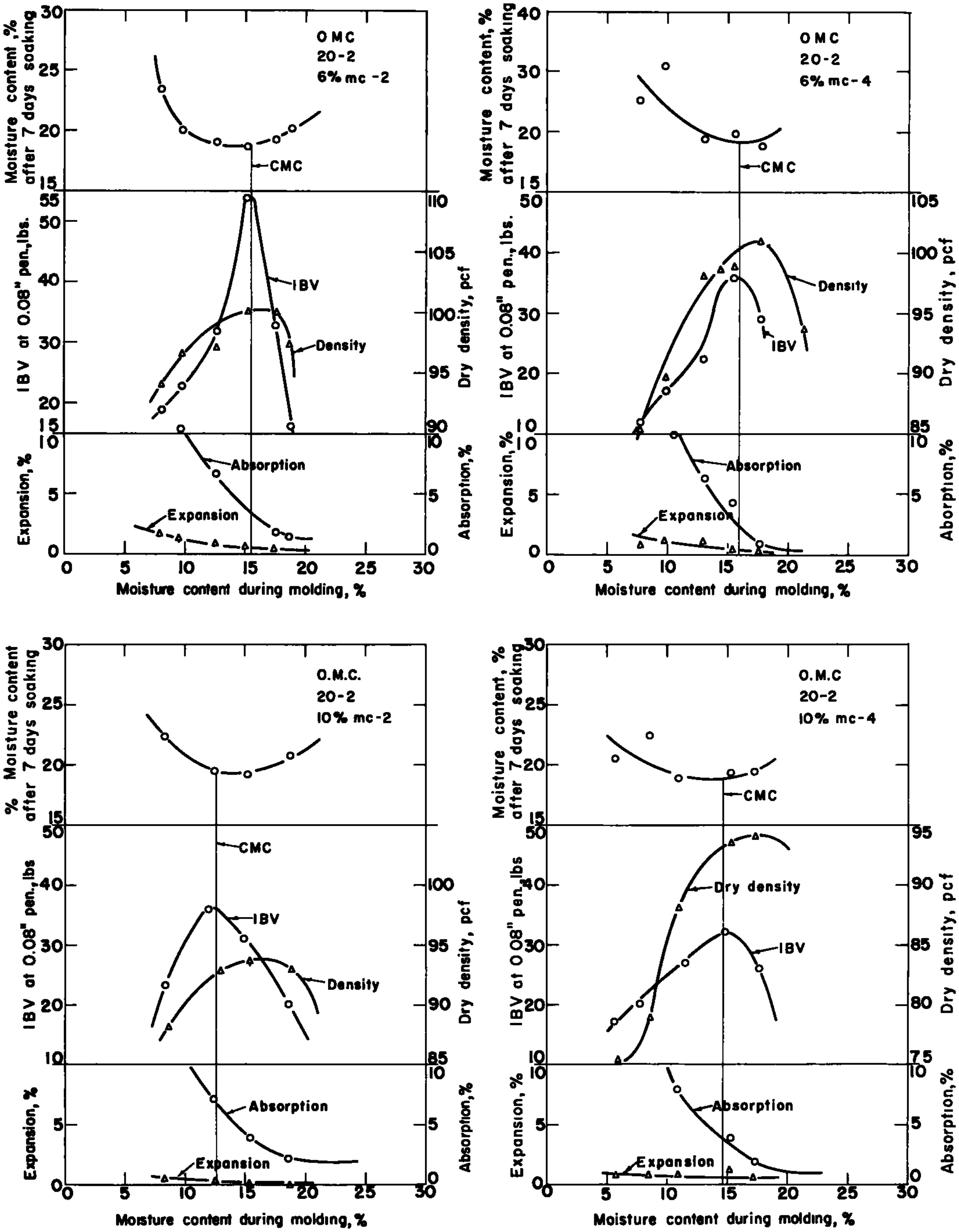



Figure 6. Graphs of moisture content during molding versus the IBV, dry density, absorption, expansion and total moisture content after 7 days soaking of soil-cutback asphalt compacted specimens. The soil-cutback asphalt compositions and the moisture content at which the mixes were mixed are listed on each graph. The amount of residual asphalt cement in 6 and 10 percent MC-2 is 4.93 and 8.2 percent, and in 6 and 10 percent MC-4 is 5.47 and 9.11 percent. The vertical line in the center of the graph indicates the CMC.

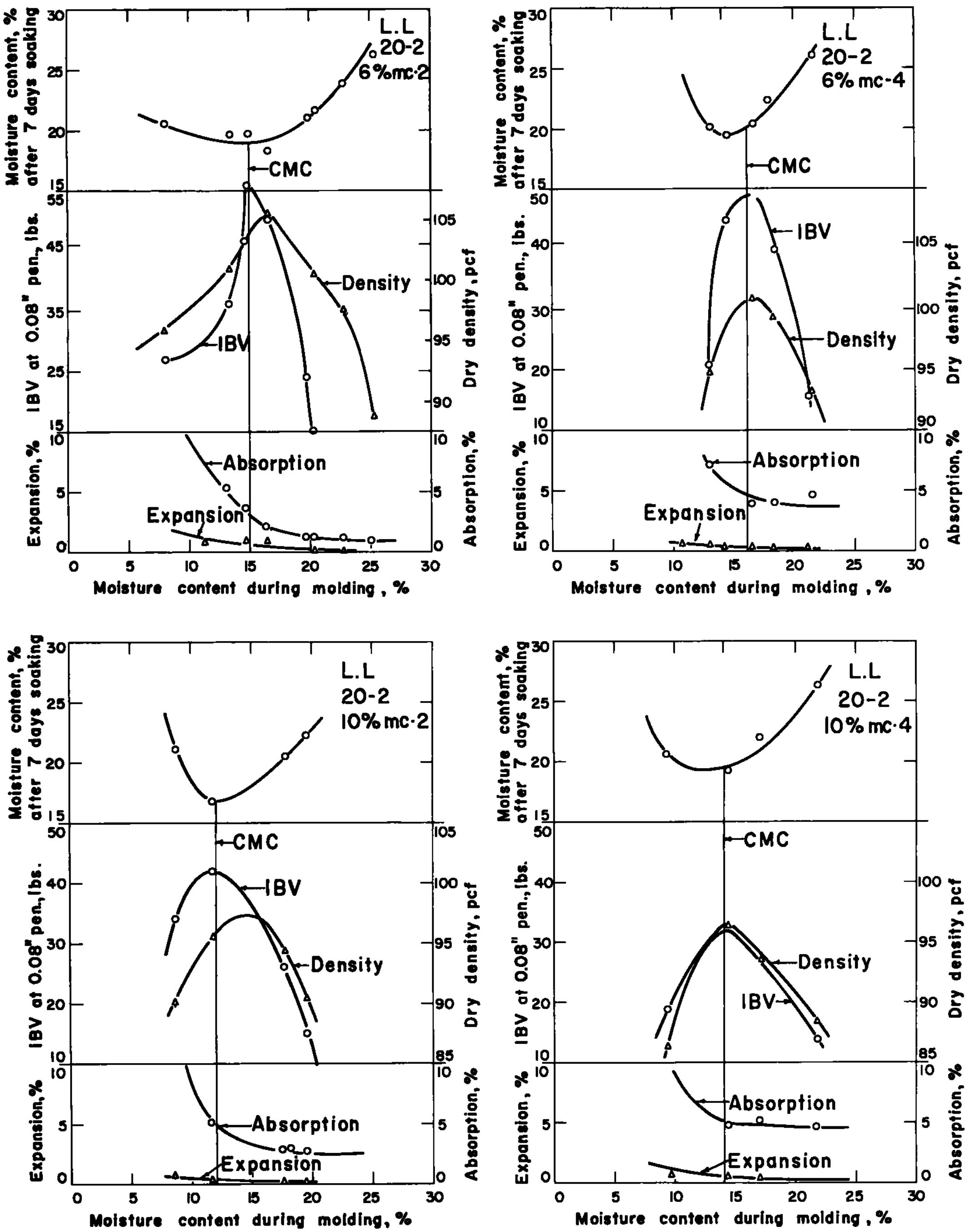



Figure 7. Graphs of moisture content during molding versus the IBV, dry density, absorption, expansion and total moisture content after 7 days soaking of soil-cutback asphalt compacted specimens. The soil-cutback asphalt compositions and the moisture content at which the mixes were mixed are listed on each graph. The amount of residual asphalt cement in 6 and 10 percent MC-2 is 4.93 and 8.2 percent, and in 6 and 10 percent MC-4 is 5.47 and 9.11 percent. The vertical line in the center of the graph indicates the CMC.

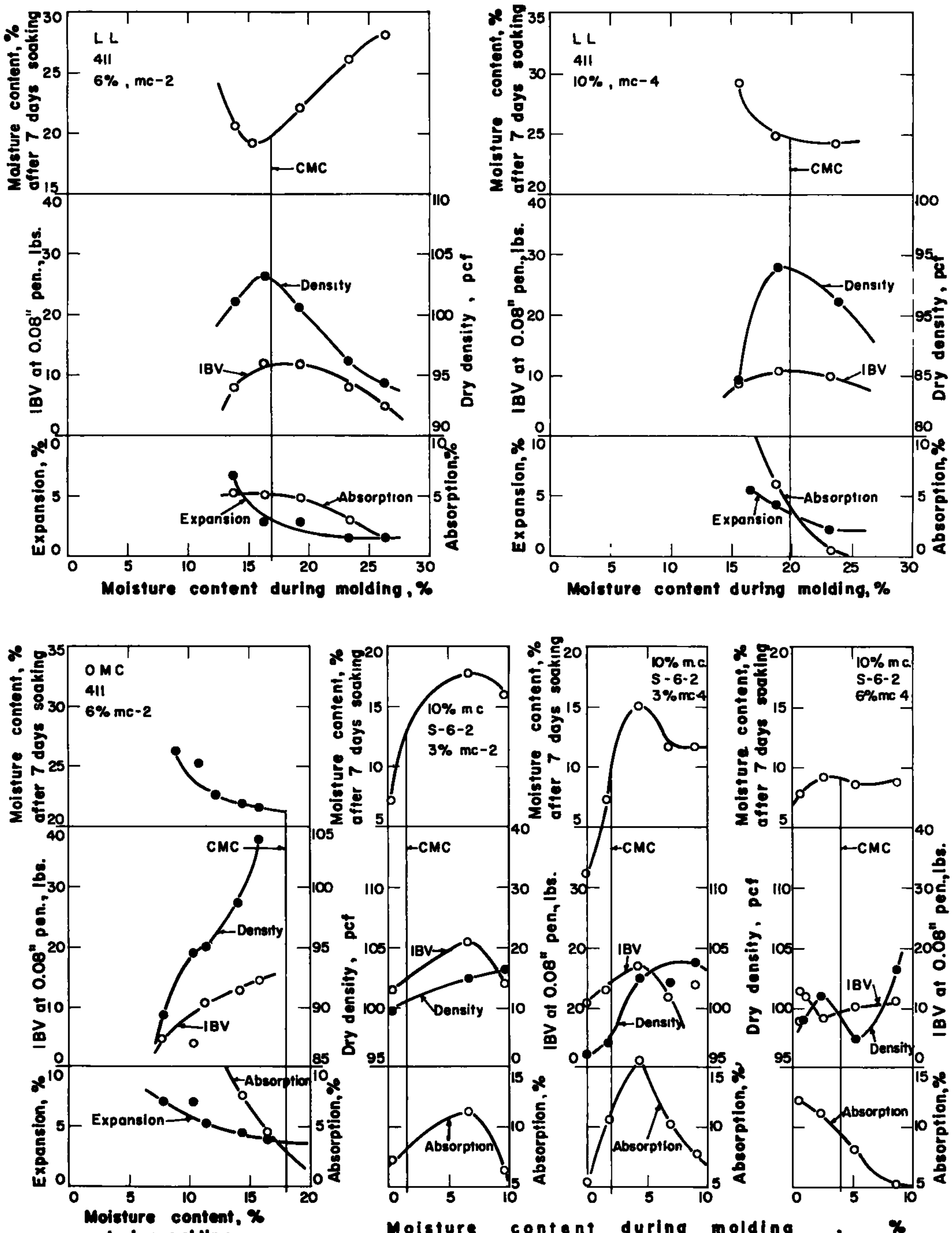



Figure 8. Graphs of moisture content during molding versus the IBV, dry density, absorption, expansion and total moisture content after 7 days soaking of soil-cutback asphalt compacted specimens. The soil-cutback asphalt compositions and the moisture content at which the mixes were mixed are listed on each graph. The amount of residual asphalt cement in 6 percent MC-2 is 4.93 percent. The vertical line in the center of the graph indicates the CMC.

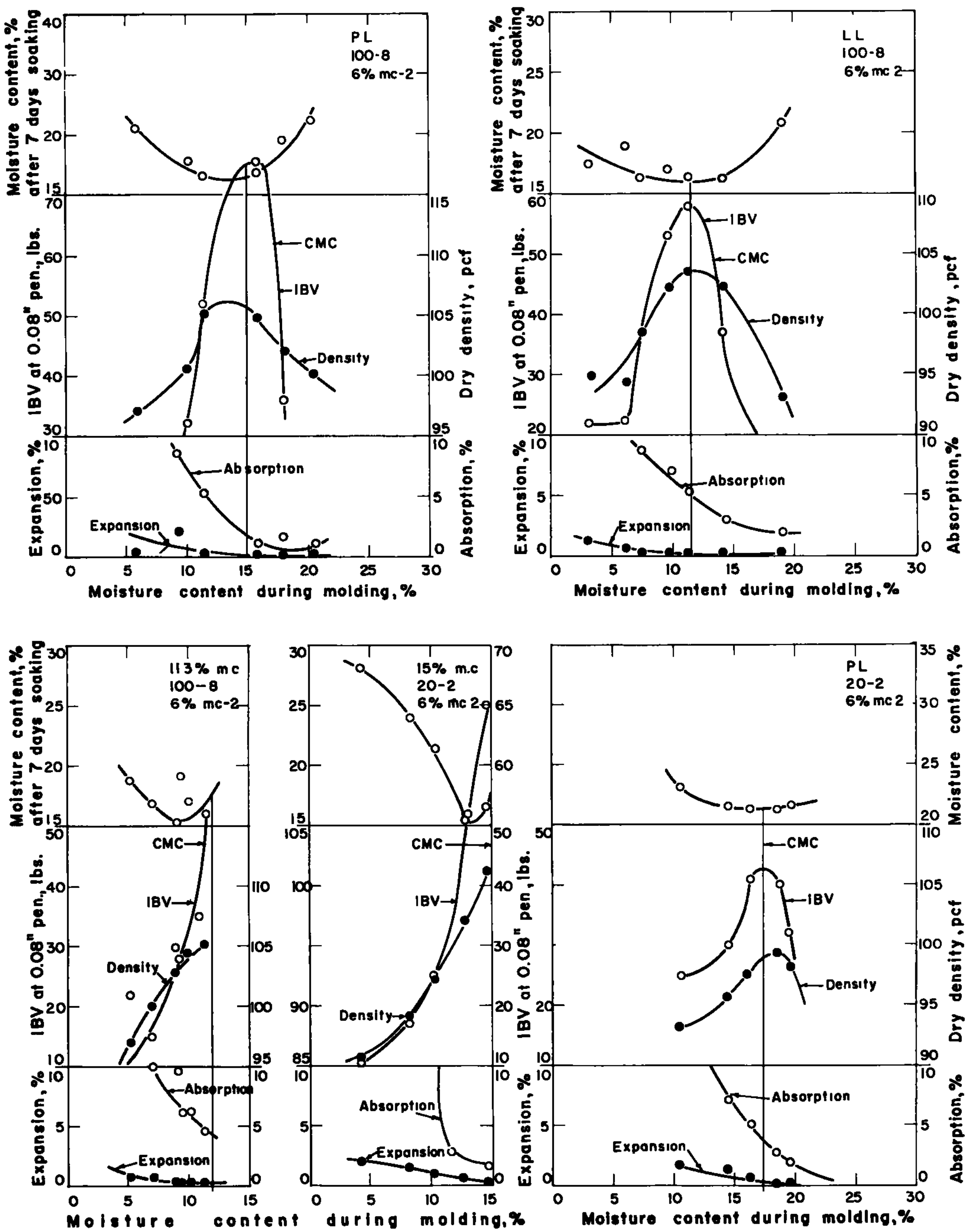



Figure 9. Graphs of moisture content during molding versus the IBV, dry density, absorption, expansion and total moisture content after 7 days soaking of soil-cutback asphalt compacted specimens. The soil-cutback asphalt compositions and the moisture content at which the mixes were mixed are listed on each graph. The amount of residual asphalt cement in 3, 6 and 10 percent MC-2 is 2.47, 4.93 and 8.2 percent, and in 3, 6 and 10 percent MC-4 is 2.7, 5.47 and 9.11 percent. The vertical line in the center of the graph indicates the CMC.

TABLE 5

BEST ATTAINABLE VALUES OF IBV, DENSITY AND TOTAL 7 DAY SOAKED MOISTURE CONTENT AT CMC USING MC-2 CUTBACK ASPHALT

| | | Process I | | | Process II | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Soil No. | Amount of Asphalt, % | IBV lb | Density pcf | Total Moisture Content, % | M.C. During Mixing % | M.C. During Mixing Corresponds to | IBV lb | Density pcf | Total Moisture Content, % |
| 20-2 | 6 | 71 | 105 | 16.8 | 15.0 | | 65 | 102 | 17.5 |
| | | | | | | O.M.C. | 54 | 100 | 18.9 |
| | | | | | | P.L. | 42 | 99 | 21.2 |
| | | | | | | L.L. | 56 | 104 | 19.0 |
| | 10 | 54 | 98 | 14.8 | | O.M.C. | 36 | 93 | 19.4 |
| | | | | | | L.L. | 42 | 96 | 16.9 |
| 100-8 | 6 | 78 | 107 | 15.3 | 11.3 | | 52 | 105 | 17.6 |
| | | | | | | P.L. | 75 | 106 | 16.5 |
| | | | | | | L.L. | 69 | 104 | 16.0 |
| 411 | 6 | 17 | 104 | 18.3 | | O.M.C. | 15 | 105 | 21.3 |
| | | | | | | L.L. | 12 | 103 | 19.7 |
| S-6-2 | 3 | 10 | 106 | 7.0 | | | 15 | 101 | 13.0 |

TABLE 6

BEST ATTAINABLE VALUES OF IBV, DENSITY AND TOTAL 7 DAY SOAKED MOISTURE CONTENT AT CMC USING MC-4 CUTBACK ASPHALT

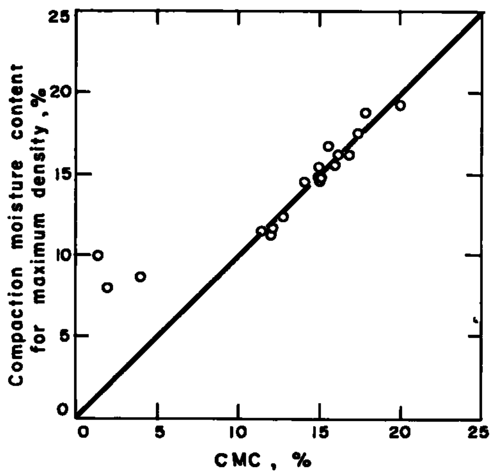
| | | Process I | | | Process II | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Soil No. | Amount of Asphalt, % | IBV lb | Density pcf | Total Moisture Content, % | M.C. During Mixing % | M.C. During Mixing Corresponds to | IBV lb | Density pcf | Total Moisture Content, % |
| 20-2 | 6 | 51 | 105 | 15.9 | | O.M.C. | 36 | 100 | 19.2 |
| | | | | | | L.L. | 50 | 101 | 20.1 |
| | 10 | 43 | 96 | 11.5 | | O.M.C. | 32 | 93 | 19.8 |
| | | | | | | L.L. | 32 | 97 | 19.5 |
| 411 | 10 | 12 | 90 | 22.3 | | L.L. | 11 | 94 | 24.5 |
| S-6-2 | 3 | 17 | 105 | 17.0 | 10.0 | | 24 | 98 | 10.0 |
| | 6 | 19 | 105 | 14.6 | 10.0 | | 10 | 99 | 9.2 |

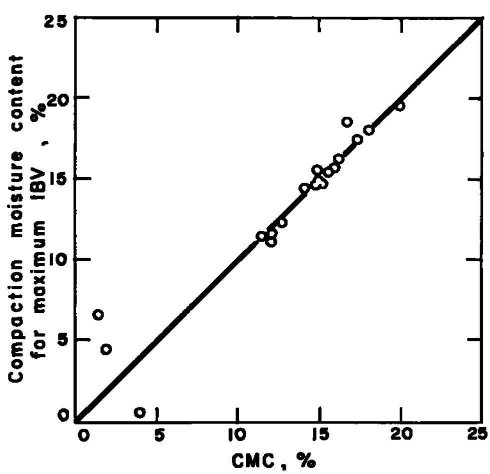
the application and use of cutback asphalt soil stabilization to medium to non-plastic soils.

## Distribution of Asphalt

The water in soil-cutback asphalt mixtures not only aids in attaining maximum densities but also aids in obtaining even distribution of asphalt throughout the soil mass. A study of this was made by mixing batches of soil with a constant percentage of asphalt and varying amounts of water from one percent to percentages slightly above the liquid limit of the soil. Specimens were prepared by compaction and curing. Curing was done to remove moisture so that the areas containing cutback asphalt showed a high contrast to the areas containing little or no cutback asphalt. Photographs of specimens from each batch were made and are shown in Figures 11 to 16. The percentages indicated below each photograph represent the moisture content that lies the closest (of those shown) to the compromise moisture content as determined from the experimental data.

Figures 11 to 15, which are photographs of compacted cutback asphalt treated loess and glacial till, show that the asphalt tends to be locally concentrated and poorly distributed at low mixing moisture contents, as indicated by the dark areas which contain the highest cutback asphalt concentrations. The distribution of cutback asphalt improves as the amount of mixing water is increased, and the most uniform distribution appears to be somewhere in the neighborhood of the liquid limit of the soil. No difference in distribution pattern was noticed between MC-2 and MC-4 treatment of these soils.



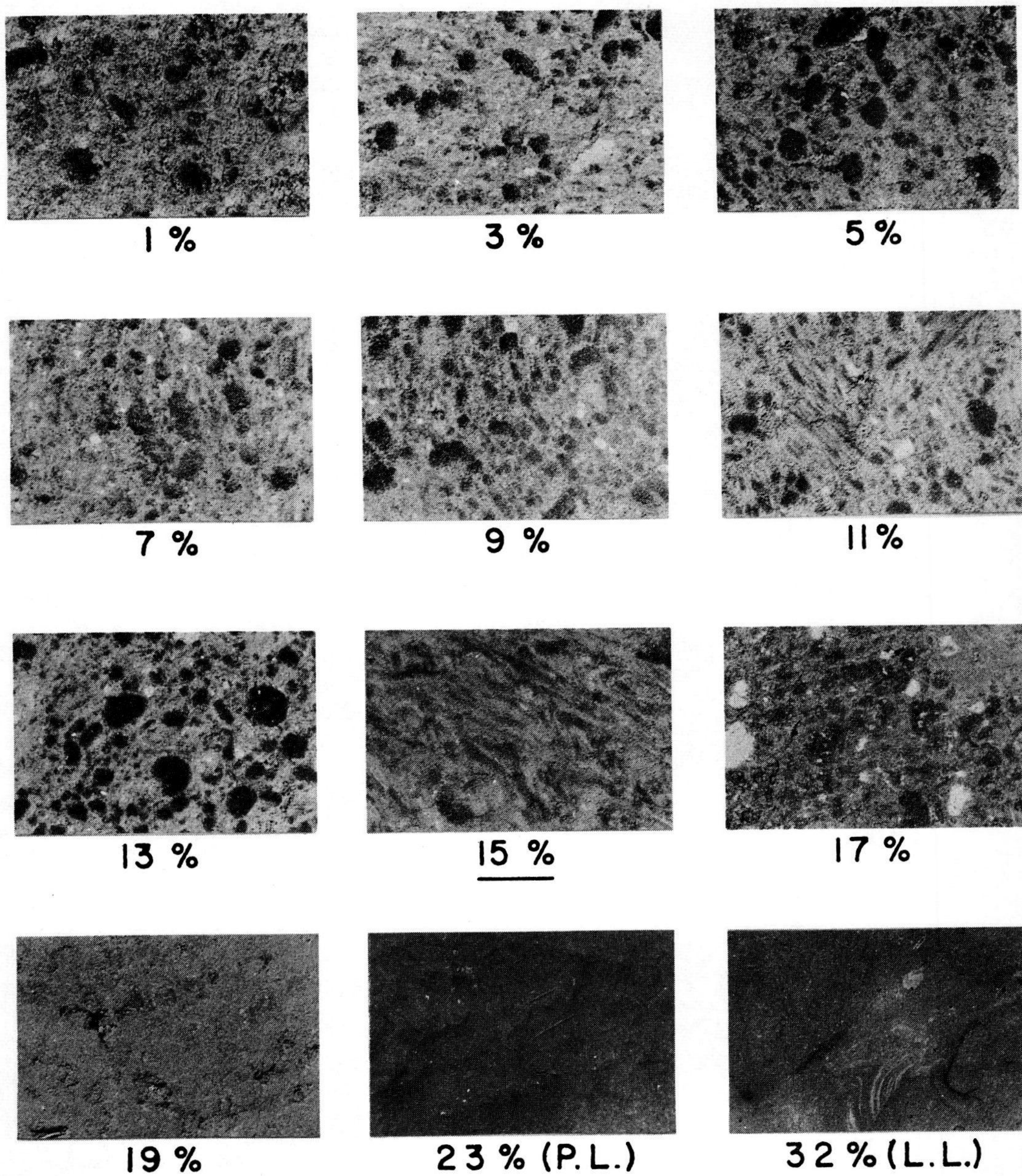




**Process II**

Figure 10. Graph comparing compaction moisture content for maximum standard Proctor density and compaction moisture content for maximum IBV with the compromise moisture content. Exact correlation of the experimental data would fall on the indicated 45-deg line. This relation holds true for the silty and clayey soils used in this investigation.

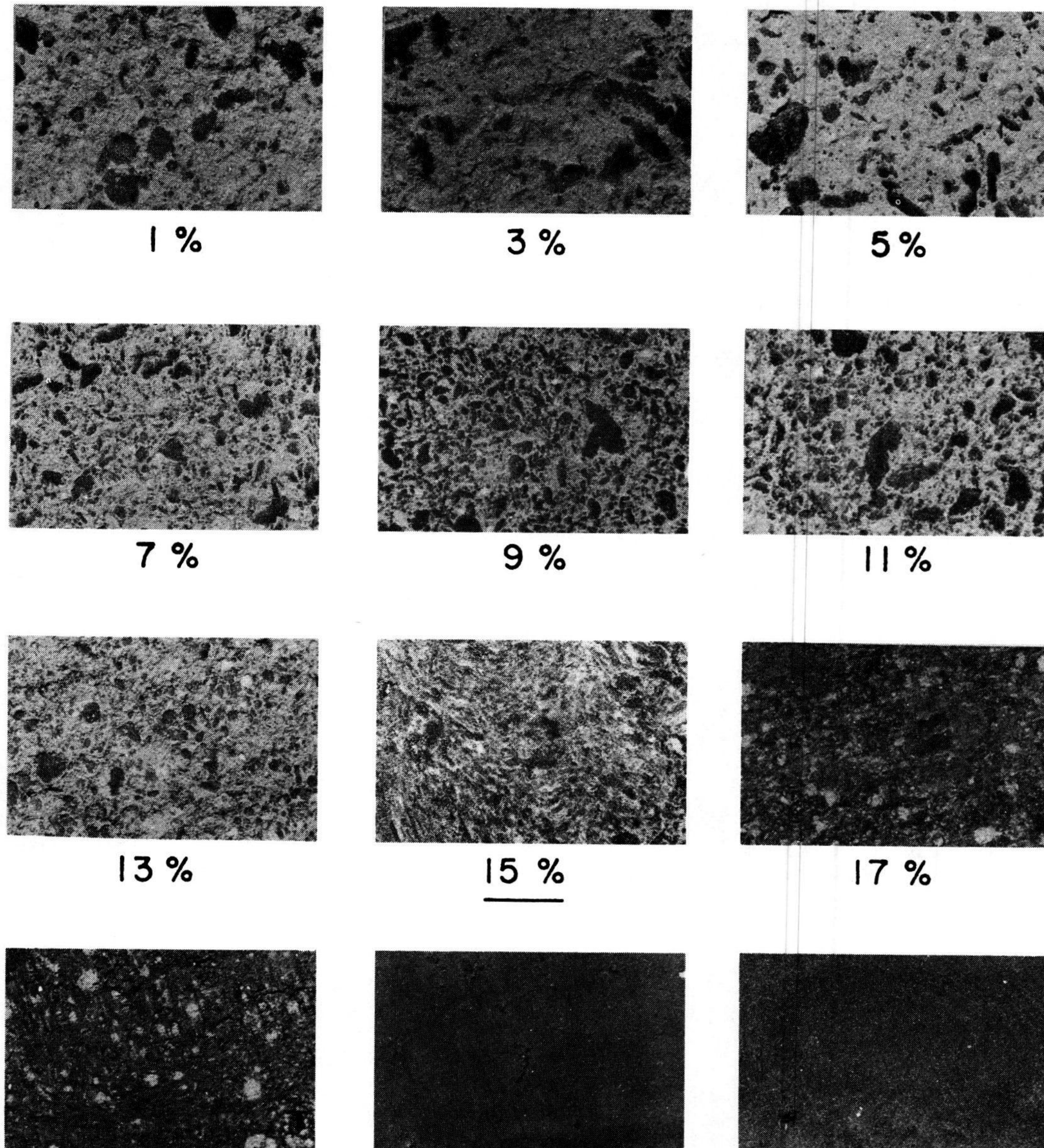
Loess. The photographs show that the compromise moisture content (CMC) for the two loess (20-2 and 100-8) soils occurs at about the mixing moisture content where the asphalt appears to be streaked or smeared in the soil rather than uniformly distributed. The CMC also lies well below the plastic limit of the soil. Mixing moisture contents above the CMC produce much more uniform distribution of asphalt but evidently the asphalt films resulting from mixing in this moisture range do not produce optimum cohesion and lower permeability. The loess soils mixed easily with asphalt at all moisture contents.

Glacial Till. The photographs



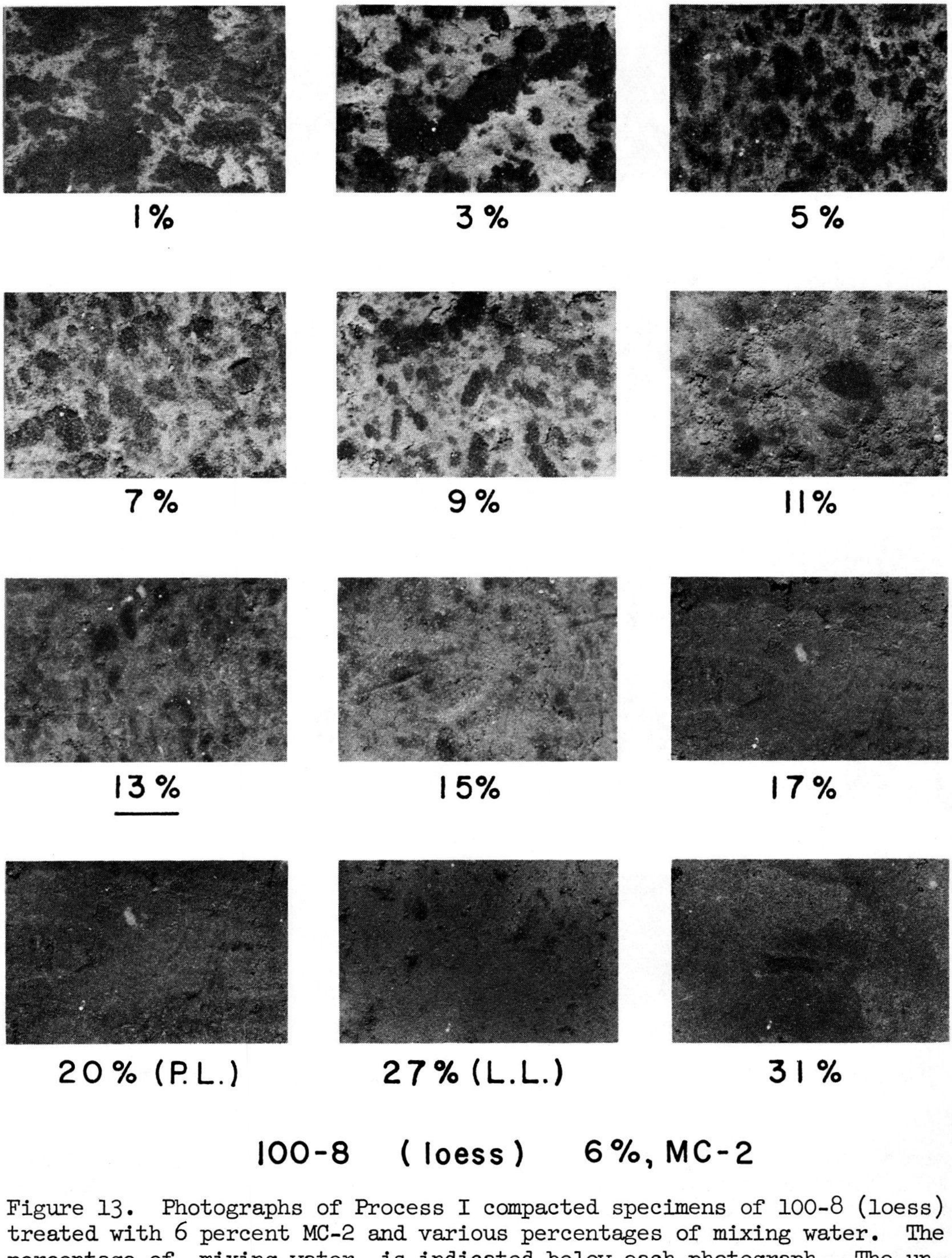

**20 - 2 (loess) 6 %, MC-2**

Figure 11. Photographs of Process I compacted specimens of 20-2 (loess) treated with 6 percent MC-2 and various percentages of mixing water. The percentage of mixing water is indicated below each photograph. The underlined percentage indicates the moisture content that is closest to the CMC of the mixture shown. Photographs of specimens mixed at the plastic limit and the liquid limit of the soil are indicated by the initials P.L. and L.L. following the appropriate moisture percentages. The residual asphalt cement content is 4.93 percent.




20-2 (loess) 6%, MC-4

Figure 12. Photographs of Process I compacted specimens of 20-2 (loess) treated with 6 percent MC-4 and various percentages of mixing water. The percentage of mixing water is indicated below each photograph. The underlined percentage indicates the moisture content that is closest to the CMC of the mixture shown. Photographs of specimens mixed at the plastic limit and the liquid limit of the soil are indicated by the initials P.L. and L.L. following the appropriate moisture percentages. The residual asphalt cement content is 5.47 percent.




100-8 (loess) 6%, MC-2

Figure 13. Photographs of Process I compacted specimens of 100-8 (loess) treated with 6 percent MC-2 and various percentages of mixing water. The percentage of mixing water is indicated below each photograph. The underlined percentage indicates the moisture content that is closest to the CMC of the mixture shown. Photographs of specimens mixed at the plastic limit and the liquid limit of the soil are indicated by the initials P.L. and L.L. following the appropriate moisture percentages. The residual asphalt cement content is 4.93 percent.

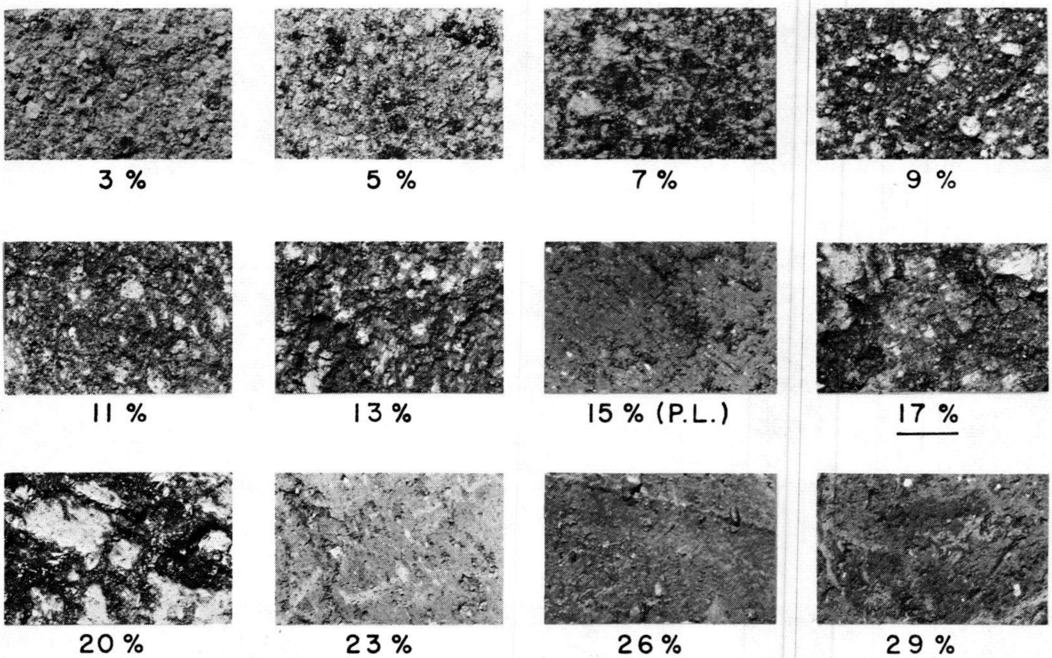



Figure 14. Photographs of Process I compacted specimens of 411 (glacial till) treated with 6 percent MC-2 and various percentages of mixing water. The percentage of mixing water is indicated below each photograph. The underlined percentage indicates the moisture content that is closest to the CMC of the mixture shown. Photographs of specimens mixed at the plastic limit and the liquid limit of the soil are indicated by the initials P.L. and L.L. following the appropriate moisture percentages. The residual asphalt cement content is 4.93 percent.

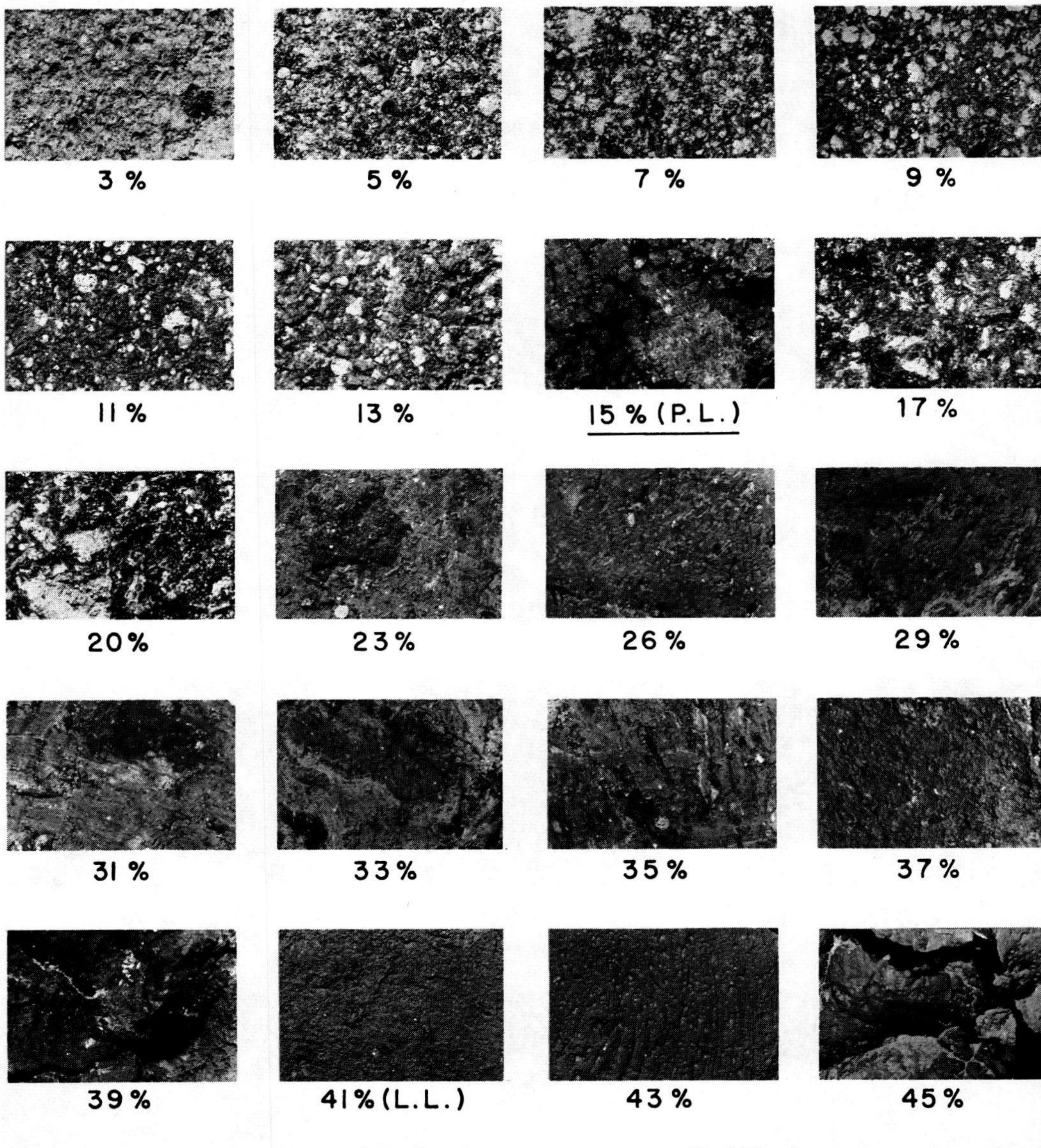



Figure 15. Photographs of Process I compacted specimens of 411 (glacial till) treated with 6 percent MC-4 and various percentages of mixing water. The percentage of mixing water is indicated below each photograph. The underlined percentage indicates the moisture content that is closest to the CMC of the mixture shown. Photographs of specimens mixed at the plastic limit and the liquid limit of the soil are indicated by the initials P.L. and L.L. following the appropriate moisture percentages. The residual asphalt cement content is 5.47.

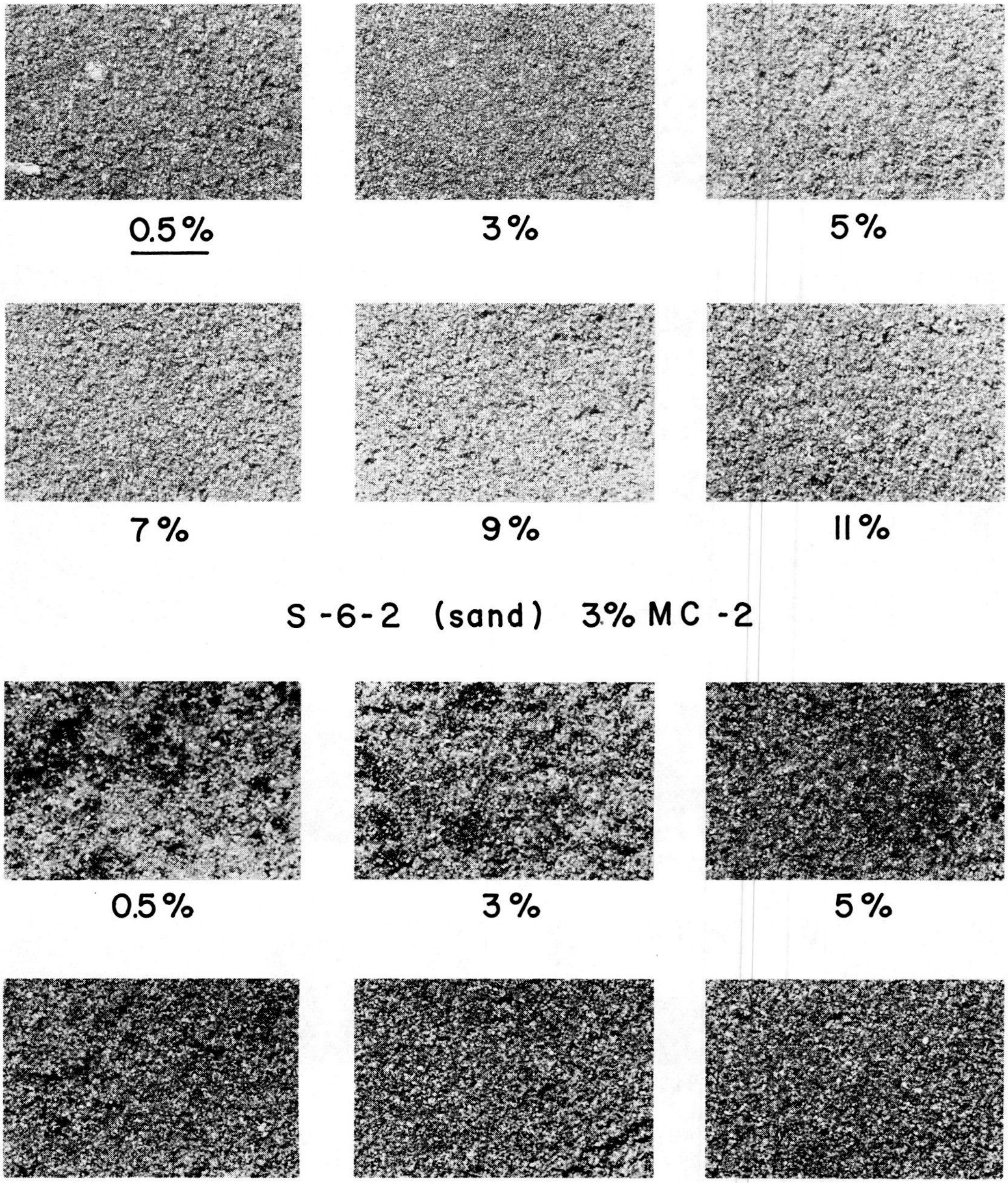



Figure 16. Photographs of Process I compacted specimens of S-6-2 (sand) treated with 3 percent MC-2 and MC-4 and various percentages of mixing water. The percentage of mixing water is indicated below each photograph. The underlined percentage indicates the moisture content that is closest to the CMC of the mixture shown. The residual asphalt cement content is 2.47 percent for MC-2 mixes and 2.74 percent for MC-4 mixes.

of the glacial till show that the asphalt is generally more poorly distributed than in the loess, but the asphalt also has a smeared appearance near the CMC, though the smeared condition is not as clearly indicated as in the loess samples. The glacial till was very difficult to mix with asphalt when the mixing moisture was in a range of 2 to 8 percent above the plastic limit of the soil. Resistance to mixing was sufficient to break the paddle of the mixing machine, and machine mixing was only carried on for about $\frac{1}{2}$ min; no supplemental hand mixing was used. The mixing limitations imposed by the highly plastic character of this soil are, no doubt, partially responsible for the poor distribution of asphalt. Extensive planes of asphalt resulted in many mixes when the system was in a moisture produced plastic state. Specimens prepared from mixtures with moisture contents above the plastic limit showed a decided tendency to develop shrinkage cracks during drying; the amount and size of the cracks increased with the mixing moisture content as shown in Figures 14 and 15.

Sand. Figure 16 shows that a different water relationship exists in the sand (S-6-2) specimens treated with MC-2 and MC-4. The top six photographs are of sand treated with MC-2 and the bottom six are of sand treated with MC-4. The MC-2 treated specimens have an estimated CMC of 1 percent whereas the MC-4 treated specimens have a CMC of 11 percent. Close examination of these photographs shows decreased coating of sand grains as the mixing water content increased above 1 percent. With MC-4 cutback asphalt better distribution was obtained as the mixing water content increased up to 11 percent. Evidently water is beneficial to asphalt distribution with MC-4 treatment; with MC-2 very little water is needed because MC-2 is not as viscous as MC-4.

Failure to coat some grains was also noted in the loess and glacial till specimens that were molded from batches mixed with higher water contents. The number of uncoated grains was small, because the failure to coat occurred mainly on the sand grains which are only a fraction of the total soil used.

## DISCUSSION

The data in the foregoing section indicate that cutback asphalt stabilization of the sandy, silty and clayey soils investigated is best accomplished by a process (Process I) in which the soil, cutback asphalt and water are mixed for a specific period of time immediately following which the mixture is compacted. The moisture content at which the silty and clayey soils are best stabilized with either MC-2 or MC-4 asphalt corresponds closely to the optimum moisture content for maximum standard Proctor density of the soil-asphalt mixture. The sandy soil required little or no moisture when stabilized with MC-2 asphalt but required enough water for maximum standard Proctor density when stabilized with MC-4.

The process (Process II) of mixing the materials at high moisture contents with a drying back period between mixing and compaction produced specimens inferior to those produced by Process I, with the quantities of cutback asphalt used. The high mixing moisture contents resulted in a cutback asphalt distribution approaching that of an intimate mix. The drying back periods were necessary to reduce the moisture content of the mixture to that needed for maximum compacted densities. Even though Process II produces better distribution of cutback asphalt than Process I, and both produce comparable compacted densities, Process I produces a compacted mixture that is more stable than that resulting from Process II.

This indicates that the most thorough cutback asphalt distribution of the percentages used does not insure the highest stability in silty and clayey soils. Visual evidence indicates that for sandy soils the moisture content for maximum density and the moisture content for maximum cutback asphalt distribution are coincident.

The photographic study of the effect of moisture content on the distribution of asphalt is not as precise as the quantitative moisture-property studies, because the photograph showing best distribution of cutback asphalt must be estimated. However, the general range of moisture content in which the best distribution of cutback asphalt occurs is quite obvious.

The findings of this investigation are generally in agreement with Benson's and Becker's (6) conclusions that the maximum stability of cutback asphalt stabilized soil is reached at some definite degree of cutback asphalt distribution less than an intimate mix. The structure of the soil-cutback asphalt system at the point of maximum stability is believed to consist of small irregular soil aggregates within which there is no effective waterproofing or cementing bituminous material. The surfaces of the soil aggregates are covered with asphalt films that vary in thickness and amount of coverage. Compaction of such a system produces a dense mass of individually waterproofed soil aggregates.

The basic structural system is thought to be established during the process of mixing. The cutback asphalt is first dispersed throughout the soil in small globules as a discontinuous phase, with the soil as a continuous phase. At this point in the mixing process paths through the soil-cutback asphalt system may be found which do not pass through any cutback asphalt barriers. Continued mixing causes an inversion of the phases of the cutback asphalt and the soil; the soil tends to become discontinuous, and the cutback asphalt tends to become continuous. The continuity of the cutback asphalt is probably never complete because of the small amount of cutback asphalt that can be used economically.

Benson and Becker (6) have proposed a phase-mixing theory based on the above observations. The proposal is in essence that the maximum protection occurs for a soil treated with asphaltic material when the thickest film of asphaltic material which can be closely and permanently held on or adsorbed into the surfaces of soil aggregates must contain sufficient adsorbed moisture to develop certain degrees of cohesiveness and plasticity.

The present investigation indicates that the spatial geometry of the Benson and Becker theory is correct and that moisture must be present to produce cohesiveness and plasticity in the soil aggregates. This investigation also indicates that moisture must be present for the purpose of attaining near maximum density in the individual soil aggregates and as an aid in the distribution of cutback asphalt. Maximum density of the soil aggregates must occur at nearly the same moisture content at which maximum density of the soil-cutback asphalt mass occurs because, for the percentages of cutback asphalt used, over-all density is changed very little due to differences in specific gravity. The density of the mass is dependent mainly on the density of the individual soil aggregates.

Any amount of water greater than that required for maximum densities serves only to aid in obtaining a degree of distribution of cutback asphalt approaching an intimate mix. The excess water must then be evaporated in order to obtain good densification by compaction. Evidently, enough mixing to give high degrees of asphalt distribution results in small soil aggregates in which some of the strength properties are destroyed. The smaller the aggregates the higher the total surface area. Coverage of a high surface area with asphalt results in asphalt films that are too thin for optimum waterproofing and cohesion.

A soil aggregate particle coated with cutback asphalt is penetrated to some depth by the constituents of the bituminous material. The core of such a particle remains in its natural untreated state and retains its inherent strength properties. The soil material of the outer layer of the particle has lost its natural cohesion, and the frictional properties have been reduced due to the waterproofing and lubricating effects of cutback asphalt. A treated particle may be weaker than an untreated particle of equivalent size; however, the treated particle will be the most waterproof. The strength data and the photographs indicate that as individual soil aggregate particles grow smaller and smaller the strength of the mass also decreases. This is thought to be due to reduction in size of the natural soil cores with a proportional loss in strength, because the depth of asphalt penetration into a soil aggregate will be the same regardless of the size of the aggregate particles. A very small particle is apt to be thoroughly penetrated by cutback asphalt and will then possess only the cohesive strength of the asphalt.

The following tabulation of generalized physical properties and phases of the soil and the asphalt within compacted soil-cutback asphalt mixtures have been derived from the data:

SOIL

| Little or No Mixing Water | Intermediate Amounts of Mixing Water | High Amount of Mixing Water |
|---|---|---|
| Large aggregates | Medium aggregates | Small aggregates |
| Low strength | Maximum strength | Low strength |
| Low density | Maximum density | Low density |
| No shrinkage | Little shrinkage | High shrinkage |

CUTBACK ASPHALT

| Little or No Mixing Water | Intermediate Amounts of Mixing Water | High Amount of Mixing Water |
|---|---|---|
| Globules | Thick films | Thin films |
| Discontinuous phase | Semi-continuous phase | Continuous phase |
| Low cohesion | Medium cohesion | High cohesion |
| Low waterproofing | High waterproofing | Low waterproofing |

This tabulation indicates that the optimum properties of a compacted soil-cutback asphalt mixture lie within the intermediate range of mixing moisture contents. The determination of the compromise moisture content (CMC) indicates a mixing water content at which the best combination of properties results. The degree of distribution of cutback asphalt is a function of the amount of mixing water, better distribution being obtained as the amount of water is increased with this type of mixing. The CMC also represents a mixing moisture content at which a compromise degree of asphalt distribution occurs.

Cutback asphalt stabilization of the soil types investigated is best accomplished as a general rule by mixing the moist soil and the asphalt at the water content needed for maximum standard Proctor density of the optimum results, and it is essential to maximum stability that compaction be carried out immediately following mixing.

## SUMMARY AND CONCLUSIONS

The effects of water content during mixing and during compaction of soil-cutback asphalt mixtures on the physical properties of the compacted product have not been clearly defined in the past. The primary objectives of this investigation have been to study and evaluate these effects.

The following conclusions concerning cutback asphalt soil stabilization are made on the basis of observations and results of the investigation. It is believed that the conclusions should apply in general to all soils of similar textural and mineralogical composition.

1. The degree of cutback asphalt dispersion in a soil mass is a function of the amount of water present during mixing. The resulting mixture varies from poor, when little water is present, to a quasi-homogenous or intimate mix when a high percentage of water is present.
2. Compaction of a soil-cutback asphalt-water system immediately following mixing produces a more stable product than a procedure in which a drying back period is included between mixing and compaction.
3. An intimate mix does not produce the most desirable stability properties of the compacted mixture.
4. The percentage of mixing water required to produce maximum IBV, maximum standard Proctor density, minimum total moisture content after 7 days' immersion, and minimum expansion in compacted specimens is different for each property mentioned. However, the range of water content over which these minimum or maximum properties occur is only several percent.
5. A compromise moisture content (CMC) for mixing may be found at which the variance from the best value of the properties mentioned in Conclusion 4 will be a minimum. The CMC is most advantageously determined by the method of first powers.
6. The CMC is very close to the mixing moisture content at which maximum standard Proctor density of the soil-cutback asphalt-water system occurs. The moisture content corresponding to maximum standard Proctor density of the soil-cutback asphalt-water mixture provides the most convenient and easily determined moisture control point for cutback asphalt soil stabilization.
7. The value of the CMC or standard Proctor optimum moisture depends on the type of soil, the type and amount of cutback asphalt used.
8. The "fluff-point" moisture content and the mixing moisture content required to produce an optimum combination of stability properties do not correspond.
9. The best over-all stability results for a sandy soil and MC-2 cutback asphalt are obtained when little or no mixing moisture is used; however, when treating with MC-4 cutback asphalt the moisture corresponding to the CMC or standard Proctor optimum moisture content should be present during mixing.
10. Quasi-homogeneous soil-cutback asphalt systems can be produced

with silty and clayey soils if the amount of mixing water used is at least equivalent to the liquid limit of the soil being mixed. Mixing of clayey soil-water-asphalt systems is nearly impossible within reasonable mechanical limitations when the moisture content lies within the plastic range of the soil-water system.

11. There is an optimum duration of mixing of soil-cutback asphalt-water systems for each type of mixing equipment.

The foregoing conclusions answer the objectives of the investigation and explain the previously questionable role of water in cutback asphalt soil stabilization. The investigation should be extended to include the effects of the amount and type of cutback asphalt, emulsions, and wetting agents on the mixing water requirements of all types of soils normally encountered in the field of soil stabilization. Field trials of cutback asphalt soil stabilization should be conducted to adapt the findings of this investigation to the types of field equipment now in use.

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## REFERENCES

1. Ackerson, R. L., "Consistency Tests on Plain and Bituminous Slurries." Unpublished M.S. Thesis, Iowa State College Library, Ames, Iowa (1957).

2. Arpacioglu, Mihal, "Correlation of California Bearing Ratio with the Iowa Bearing Value." Unpublished M.S. Thesis, Iowa State College Library, Ames, Iowa (1957).

3. Beckham, W. K., "Stabilizing Clayey Soils—Soil Stabilization with Asphaltic Materials in South Carolina." Asphalt Institute, Const. Series, 40:30 (1939).

4. Benson, J. R., "Asphalt Membranes—Their Potential Use in Highway and Airfield Pavement Design." Roads and Streets, 95:78-80.

5. ____________, "Methods of Test for Asphalt Soil Stabilization Design." In American Society for Testing Materials, Procedures for Testing Soils, pp. 171-173, ASTM, Philadelphia, Pa. (Sept. 1944).

6. ____________, and Becker, C. J., "Exploratory Research in Bituminous-Soil Stabilization." Proc., Association of Asphalt Paving Technologists, 13:120-181 (1942).

7. Cape, B. E., "Test Methods Used in the Design and Control of Soil-Bituminous Mixtures in Texas." Proc., Association of Asphalt Pavong Technologists, 12:139-151 (1940).

8. Csanyi, L. H., "Bituminous Mastic Surfacings." Association of Asphalt Paving Technologists (1956).

9. Davidson, D. T., Katti, R. K., Kallman, M. E., and Gurland, J., "Correlation of the California Bearing Ratio and the Iowa Bearing Value." Presented at the ASTM Conf. (1957). (In press)

10. Endersby, V. A., "Fundamental Research in Bituminous Soil Stabilization," HRB Proc., 22:442-456 (1942).

11. Hancock, C. K., "Aluminum Sulfates and Iron Sulfates as Auxiliaries in Bituminous Stabilization of Soils." Industrial and Engineering Chemistry, 47:2230-2281 (Nov. 1955).

12. Holmes, A., and Klinger, E. W., "Field Procedure for the Design of Cutback Asphalt-Soil Mixtures." Procedures for Testing Soils, ASTM, Philadelphia, Pa. (Sept. 1944).

13. Johnson, J. C., District Engineer, Asphalt Institute, "The Use of Asphalt for Soils Stabilization." Paper presented at the National Convention of the American Road Builders' Association, Boston, Mass. (Feb. 9, 1953). (Mimeo.)

14. Katti, R. K., "Stabilization of Iowa Loess with Bituminous Materials." Unpublished M.S. Thesis, Iowa State College Library, Ames, Iowa (1954).

15. ___________, "Stabilization of Iowa Soils with Cutback Asphalt." Unpublished Ph.D. Thesis, Iowa State College Library, Ames, Iowa (1958).

16. Kelley, E. F., "Basic Principles and Economics of Subgrade Stabilization with Bituminous Materials." Asphalt Institute, Const. Series, 40:6 (1938).

17. Lafleur, J. D., Davidson, D. T., Katti, R. K., and Gurland, J., "Relationship Between the California Bearing Ratio and the Iowa Bearing Value." Iowa Eng. Exp. Sta., Ames, Iowa (1956). (Mimeo. report).

18. McKesson, C. L., "Discussion on Road Stabilization, Soil Stabilized with Emulsified Asphalt." HRB Proc., 15:358-359 (1935).

19. ______________, "Researches in Soil Stabilization with Emulsified Asphalt." Proc., ASTM, 39:1123-1139 (1939).

20. Reagel, F. V., "Stabilizing Silty Soils—Practice Developed in Missouri." Asphalt Institute, Const. Series, 40:26 (Aug. 1938).

21. Riggs, K. A., "Pleistocene Geology and Soils in Southern Iowa." Unpublished Ph.D. Thesis, Iowa State College Library, Ames, Iowa (1956).

22. Strabag Bau-A. G., "Das SchlammerVerfahren Nach Oberbach Entwicklung und Anwendung." 2 Folge Koln, Deutz., Strabag. (ca. 1954).

23. Turnbull, W. J., and Foster, C. R., "Bituminous Stabilization." In Conference on Soil Stabilization, Cambridge, Mass., June 18, 1952, pp. 122-136, MIT, Cambridge, Mass. (ca. 1952).

24. Weathers, H. C., "Stabilized Sandy Soils Practical Development in Florida." Asphalt Institute, Const. Series, 40:13 (1938).

25. Wehner, A. J., "Earth Stabilization from the Field." American Road Builders' Association, Bul. No. 60 (1939).

26. Winterkorn, H. F., "Fundamental Approach to the Stabilization of Cohesive Soils," HRB Proc., 28:415-422 (1948).

27. _________________, "Physico-Chemical Factors of Importance in Bituminous-Soil Stabilization." Proc., Association of Asphalt Paving Technologists, 2:206-257 (1940).