Optimization of Clay Subgrade Compaction in Arid Regions

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The purpose of this paper is to discuss the most beneficial density and moisture content for compacted clay subgrade in arid regions. The present specifications do not consider environmental changes after the soil is in place under a roadway, and the density required is based on an arbitrary compactive effort. There are many compactive efforts available. The true problem is to determine which compacted dry density and moisture content will give the highest strength and minimum swell when the material shrinks due to drying before the base and pavement are installed and then is exposed to capillary wetting after the pavement is installed and evaporation is prevented. Research results are presented, and a method of specifying compacted densities is suggested.

•THE WORD CLAY has an ominous sound to most highway engineers. The material is generally considered to have little or no shear strength and it often displays unusual large swelling characteristics on exposure to moisture. However, highways must be constructed through areas where clay soils exist, and maximum use must be made of the natural material, consistent with sound engineering practice.

Highway construction problems caused by the presence of clay soils are often multiplied in the arid and semi-arid areas of the Southwest. The natural environment has conspired to make these materials as inconspicuous as possible to the casual observer. Clay in its natural state is highly overconsolidated and displays a tremendous cohesive strength, primarily due to its desiccated condition. Vertical standing walls several tens of feet high can be seen along erosion channels, or arroyos, throughout the area. The infrequent precipitation serves to preserve the illusion of inherent stability and strength.

Vast sedimentary deposits, consisting of Triassic, Jurassic, and Permian "Red Beds," occur in large areas of Arizona, New Mexico, Texas, and Oklahoma. These deposits are composed to a large extent of clay minerals, predominantly montmorillonite. Though the percent of clay material present in the soil varies considerably from one location to another, the general characteristics are quite similar.

Casual treatment of this material by the highway engineer during the investigation, design, and construction phase is an invitation to disaster. However, a thorough investigation of the characteristics of the clay material, a realistic assessment of its performance under varying environmental conditions, and close control of construction operations in the field can usually insure a satisfactory highway structure.

The abundance of the Triassic and Jurassic "Red Bed" deposits in New Mexico (approximately 12,000 sq mi or 9 percent of the state's area) prompted this laboratory investigation of a typical clay soil. The material selected came from the vicinity of Fort Wingate, N. M., and was readily available in sufficient quantities for laboratory purposes without reuse of the material being necessary. The Fort Wingate clay has a liquid limit of 47 and a plastic limit of 26. A similar material from the vicinity of

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Santa Rosa, N. M., has a liquid limit of 30 and a plastic limit of 21. The activity number (the plasticity index divided by the percent of clay) for both these materials is approximately 1.3.

ENVIRONMENT UNDER A PAVEMENT

The environment for a clay subgrade in an arid region is completely and drastically changed when an impervious wearing surface is placed over it. All vertical evaporation is terminated. However, any precipitation is drained to the shoulder where it usually finds easy access through the base course to the clay subgrade. Moisture then migrates via the pores or capillary passages from the wetter to the dryer subgrade. The equilibrium moisture content eventually reached in the clay subgrade under a pavement approaches 95 to 98 percent saturation. If the clay subgrade has large volume change characteristics, the surface is bodily lifted upward. At the same time, its shear strength decreases and a flexible surface is rutted under loads it was previously capable of sustaining.

OBJECTIVE OF LABORATORY INVESTIGATION

The principal objective of this investigation was to determine if there exists an initial dry unit weight and moisture content to which a subgrade should be compacted in the field that would insure the highest strength and lowest swell after the subgrade is dried and then exposed to capillary wetting. Although it has been recognized for several years by some authorities that a swelling clay must be treated carefully and field compaction must be controlled more closely than for other materials (13, 14), it is not uncommon to find a requirement that material be placed at some arbitrary percent of maximum density as determined by AASHO Designations: T 99 or T 180. The moisture content at which this density is to be obtained is very seldom, if ever, specified since the engineer intuitively feels that there is a very narrow range of moisture con- nts under which acceptable densities can be obtained.

Some criteria must be established to achieve adequate performance characteristics of compacted clay subgrades. Since the moisture content is likely to increase and the clay is going to change volume by swelling, it should be placed at some unit weight and moisture content that will minimize this effect. At the same time, the clay should possess the highest possible shear strength after swelling. Usually, several days or weeks elapse before the base course and wearing surface are placed over a prepared subgrade. In the arid Southwest, the clay subgrade shrinks rapidly and becomes very hard. If no effort is made to prevent this shrinkage, any criteria for volume change should be based on the volume of the clay in its desiccated condition.

DESCRIPTION OF TESTS

Standard laboratory procedures were used in preparing the material for determining laboratory compaction density-moisture relationships. Three compactive efforts were used to develop a family of compaction curves, rather than a single compactive curve. Five sets of samples, each at different moisture contents, were prepared for each compactive effort. Each set consisted of four specimens molded at the same moisture-density relationship. These were then used to determine the strength and change in volume while in one of the following conditions:

1. Immediately after molding;
2. After molding, subjected to capillarity without any opportunity for drying;
3. After molding, allowed to dry at ambient room temperature and humidity; and
4. After molding and air drying, subjected to capillary wetting.

The volume and moisture contents were determined after each exposure to a particular environment.

HARVARD COMPACTION APPARATUS

The Harvard compaction apparatus was chosen to determine the relationship between y unit weight and molded moisture content. The apparatus is a miniature kneading type, and the compactive effort can be varied by selecting an appropriate number of layers and number of tamps per layer. The tamping force depends on the type of materials compacted and the size of spring in the tamper. The mold has an internal diameter of 1.3125 in. and a height of 2.816 in. The volume of the mold is 1/454 cu ft, so the wet weight of the soil in grams is the wet unit weight of the soil in pounds per cubic foot. The samples can be molded quickly and are about the right size to be tested in unconfined compression or triaxial shear. The tamper is ½ in. in diameter. As the tamper foot is pressed into the soil, a preset compressed spring within the handle determines the amount of force applied. When a force of 40 lb was applied in this case, only a small increase in force was required for the spring to be further compressed. Although other calibrated springs can be used, only the 40-lb spring was employed in these tests. The following compactive efforts were used:

1. Compactive effort A—three equal layers, 25 tamps per layer, with the 40-lb spring pressure;
2. Compactive effort B—five equal layers, 25 tamps per layer, with the 40-lb spring pressure;
3. Compactive effort C--ten equal layers, 25 tamps per layer, with the 40-lb spring pressure.

MEASUREMENT OF STRENGTH

The unconfined compression test which is quick and simple to perform was selected to correlate strengths of the various specimens. A compressed air-operated unconfined compression device was used.

The air-dried samples failed with a sudden brittle fracture. The shear resistance recorded for these samples was the load at failure divided by the initial cross-sectional area of the sample.

The loads applied to some of the samples increased to a maximum or ultimate load, then the sample continued to be strained at a decreased load. The shear resistance recorded for these samples was the ultimate load divided by the initial cross-section area.

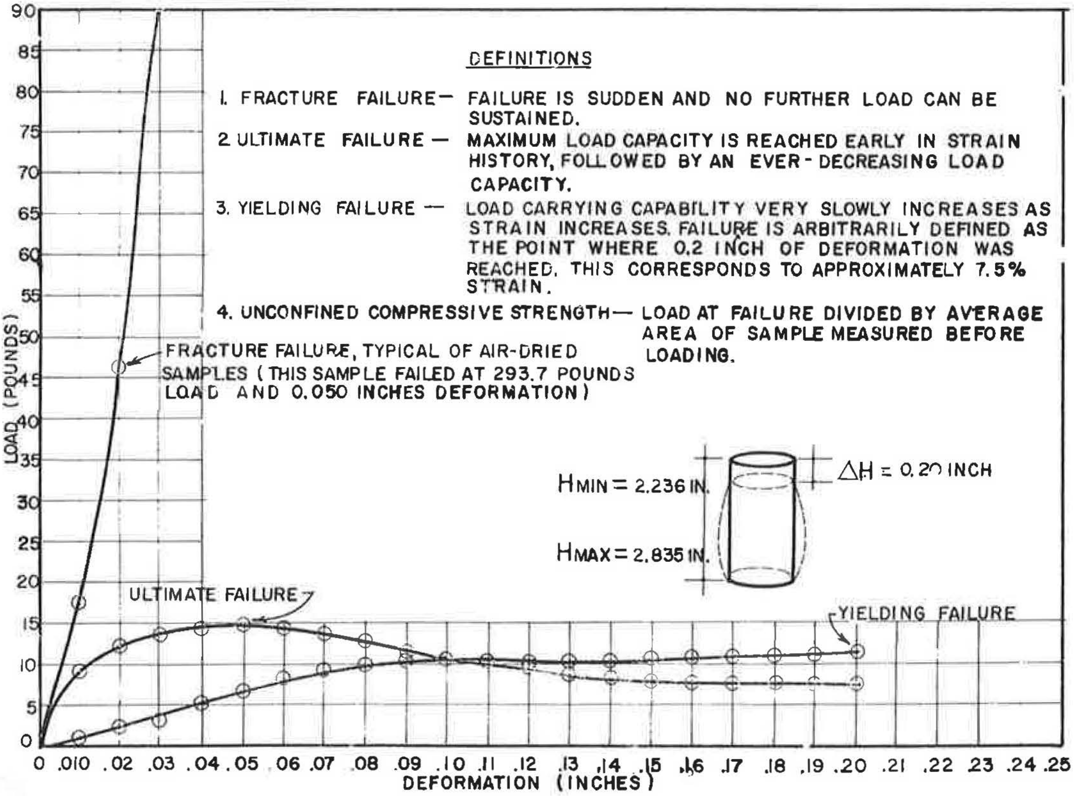
The remaining samples continued to yield under the applied load, but the load never reached an ultimate value. Failure for these samples was arbitrarily defined as the load sustained when a total deformation of 0.2 in. was recorded. This deformation corresponded to a minimum of 7 percent and a maximum of 8.9 percent strain. (The variation in strain is caused by the small differences in height of samples recorded after extrusion from the mold.) The shear resistance recorded for these yielding samples was load at 0.2-in. deformation divided by the initial cross-sectional area. Figure 1 shows typical load-deformation curves for these three types of failures.

CAPILLARY DEVICE

A diagram of the capillary device used to soak the samples is shown in Figure 2. This is a smaller model of a similar device used by the Texas Highway Department to soak their triaxial samples. By allowing the sample to absorb moisture by capillarity while the lateral pressure is about the same as in a subgrade and the vertical applied pressure approximates that applied by the base material and a paving surface, an attempt is made to simulate the conditions existing in the subgrade. The vertical applied load used in this work was 1.1 psi and the lateral load was 1.0 psi. (A better model might be selected with a ratio of lateral to vertical load of 0.4.) The soil samples were allowed to absorb moisture until the wet weight approached a constant. This occurred after 6 days.

AIR DRYING

The air drying method consisted of placing the sample in a shaded place in the laboratory until cracking began. The room temperature was about 70 F, and the relative humidity was about 25 percent. The time required for cracking to the extreme varied from 6 to 204 hr, although some samples never showed any evidence of cracking.



DEFINITIONS

1. FRACTURE FAILURE— FAILURE IS SUDDEN AND NO FURTHER LOAD CAN BE SUSTAINED.
2. ULTIMATE FAILURE — MAXIMUM LOAD CAPACITY IS REACHED EARLY IN STRAIN HISTORY, FOLLOWED BY AN EVER-DECREASING LOAD CAPACITY.
3. YIELDING FAILURE — LOAD CARRYING CAPABILITY VERY SLOWLY INCREASES AS STRAIN INCREASES. FAILURE IS ARBITRARILY DEFINED AS THE POINT WHERE 0.2 INCH OF DEFORMATION WAS REACHED. THIS CORRESPONDS TO APPROXIMATELY 7.5% STRAIN.
4. UNCONFINED COMPRESSIVE STRENGTH— LOAD AT FAILURE DIVIDED BY AVERAGE AREA OF SAMPLE MEASURED BEFORE LOADING.

Figure 1. Typical load-deformation curves.

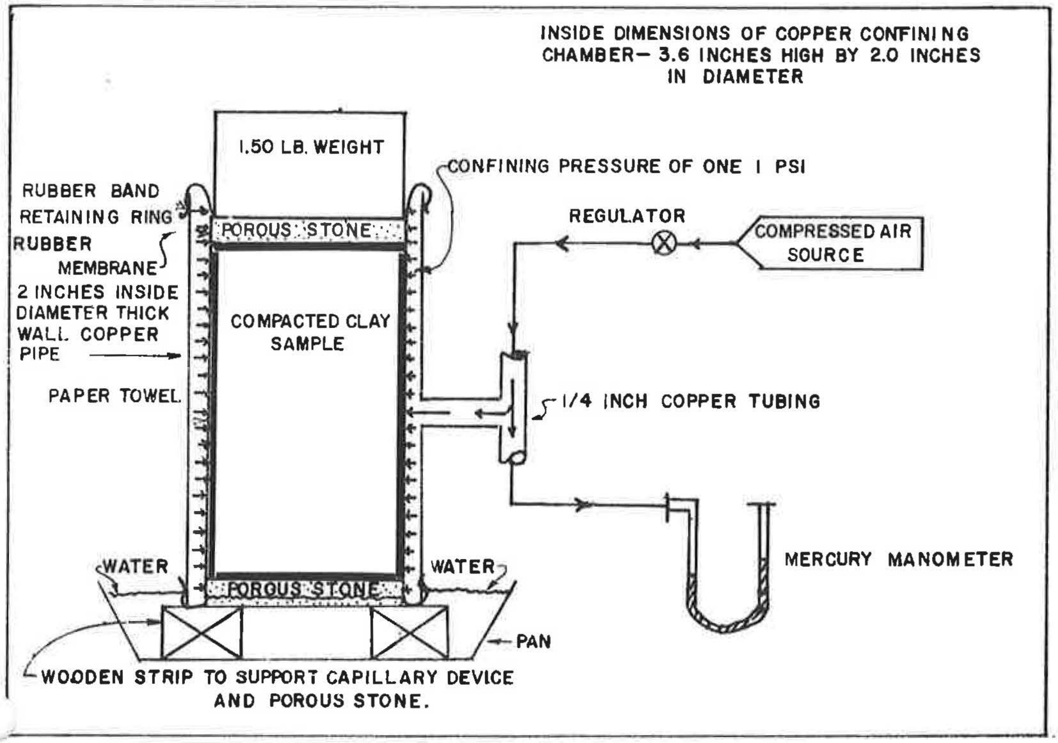


Figure 2. Schematic of capillary device.

TABLE 1

SUMMARY OF TEST RESULTS

Properties	Compactive Effort A 3 Layers, 25 Tamps, Samples:					Compactive Effort B 5 Layers, 25 Tamps, Samples:					Compactive Effort C 10 Layers, 25 Tamps, Samples:				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
As-molded															
Moisture content (%)	22.7	24.3	25.6	28.1	20.6	18.8	20.3	22.2	24.7	25.2	17.2	19.9	21.5	23.7	24.2
Dry unit wt. (pcf)	93.6	97.6	96.0	93.4	97.2	90.8	96.9	99.2	97.9	98.1	100.2	100.3	101.8	100.0	99.6
Ultimate strength (psi)	43.9	54.0	47.5	36.7	61.6	72.8	98.6	95.4	87.3	56.2	93.6	107.9	108.5	77.8	80.8
Type of failure[a]	Y	Y	Y	Y	Y	U	U	Y	Y	Y	U	U	Y	Y	Y
Strength at 2 percent strain (psi)	29.3	32.4	22.0	17.9	44.6	-	-	-	12.8	31.8	92.0	79.2	91.3	32.9	40.1
Mold, capillarity test															
Init. dry unit wt. (pcf)	96.7	97.7	96.1	93.5	96.9	91.2	98.1	98.6	98.6	97.4	98.9	101.2	103.7	101.7	100.4
Percent swell	-[b]	-[b]	4.5	11.0	-[b]	22.4	20.3	12.8	11.3	7.2	19.7	19.7	14.2	10.8	8.1
Dry unit wt. after capillarity	-[b]	-[b]	92.0	84.3	-[b]	74.6	81.5	87.4	88.6	90.8	82.7	84.6	90.7	91.8	93.0
Moisture content after capillarity (%)	43.4	33.0	32.8	35.5	45.0	43.2	29.1	32.3	33.1	31.9	37.1	34.5	32.0	30.4	31.1
Ultimate strength (psi)	0	0	3.1	6.6	0	0	3.4	7.1	8.5	8.7	2.5	3.4	7.1	8.2	9.3
Type of failure	-[b]	-[b]	Y	U	-[b]	-[b]	U	U	U	U	U	Y	Y	U	U
Capillary duration (hr)	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Strength at 2 percent strain (psi)	-[b]	-[b]	2.6	5.0	-[b]	-[b]	3.3	6.9	5.0	4.5	2.0	2.4	4.7	6.0	9.3
Mold, dry test															
Init. dry unit wt. (pcf)	94.6	97.5	96.5	92.7	98.7	92.2	96.4	98.9	97.4	97.7	99.1	100.9	104.0	100.5	99.7
Percent shrinkage	16.3	18.8	21.6	28.8	14.4	10.2	15.6	19.1	23.6	28.7	15.8	17.5	21.1	15.6	13.1
Dry unit wt. after air drying	109.6	115.9	115.6	118.6	112.9	103.1	113.1	119.3	124.5	125.8	114.9	118.6	125.9	115.8	112.7
Duration of drying (hr.)	32	32	32	32	32	120	120	120	12	48	204	204	204	12	12
Moisture content after air drying (%)	12.7	13.0	13.2	13.5	11.8	7.4	7.3	7.5	7.2	6.4	4.7	5.6	4.8	15.8	16.0
Ultimate strength (psi)	372.4	641.4	754.4	695.7	411.3	231.7	33.6	942.3	853.8	589.5	787.6	1045.1	1500	401.6	361.6
Type of failure	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Strength at 2 percent strain (psi)	351.0	421.7	495.6	387.0	383.7	231.7	33.6	942.3	654.9	589.5	787.6	916.6	931.9	231.3	231.2
Mold, dry capillarity and test															
Init. unit dry wt. (pcf)	94.7	96.2	96.6	93.3	98.3	92.8	96.2	99.3	99.2	98.2	99.4	101.5	104.6	101.3	99.5
Duration of air drying, (hr)	11	11	11	11	11	120	120	120	12	6	204	204	204	11	11
Unit dry wt. after air drying (pcf)	110.3	110.6	114.0	114.0	110.5	105.3	111.3	119.9	115.7	117.3	113.5	118.7	124.6	115.5	115.2
Moisture content after air drying (%)	12.7	15.1	15.4	15.4	12.4	7.2	5.6	6.0	13.8	15.2	4.3	5.3	5.1	14.9	14.7
Percent shrinkage	13.4	13.0	15.3	18.2	11.1	11.9	13.6	17.3	14.3	16.3	12.8	14.5	17.4	12.3	13.6
Duration of capillarity (hr)	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Unit dry wt. after capillarity (pcf)	86.3	89.8	90.4	91.0	86.0	79.4	79.8	82.3	86.6	90.3	84.1	82.5	83.8	93.2	93.2
Moisture content after capillarity (%)	33.6	31.4	30.3	29.6	32.6	42.0	40.6	38.3	32.1	30.4	40.6	36.0	36.1	30.1	30.4
Percent swell based on init. vol.	9.8	7.1	6.2	2.6	14.2	16.9	20.5	20.7	13.9	8.8	18.1	23.0	22.9	8.7	6.8
Percent swell based on air-dried vol.	26.8	23.2	25.3	25.4	28.5	32.8	39.5	45.8	32.9	29.9	35.4	43.8	48.7	24.0	23.6
Ultimate strength (psi)	4.2	5.5	9.6	9.0	3.7	0.8	0.7	0.9	2.3	6.7	1.3	1.9	2.4	10.5	9.8
Type of failure	U	U	U	U	U	Y	Y	U	U	U	Y	Y	U	U	U
Strength at 2 percent strain (psi)	3.3	3.1	9.6	8.9	2.1	0.5	0.7	0.9	2.1	6.4	0.5	1.9	2.3	9.5	9.8

[a] Definition of failures: F, fracture failure; U, ultimate failure; and Y, yielding failure. (See Fig. 2 for typical load-deformation curves.)
[b] Samples turned semi-liquid in capillarity.

After cracking started, the samples were sealed off from the air until testing. A summary of the test results is given in Table 1.

AS-MOLDED CONDITION

In Figure 3 the unconfined compressive strength is shown for the dry unit weight and moisture content in its molded state. Interpolated contours of equal shear strength connect these points. As the moisture content is varied on the dry side of the line of optimums, there is not much change in strength for a given compactive effort; the strength increases as the compactive effort increases. As the moisture content is varied on the wet side of the line of optimums for a given compactive effort, the strength decreases as the moisture content increases. For a given moisture content, the strength increases as the density increases. If the moisture content remains in the as-molded condition in a subbase, it should be required to be on the line of optimums,

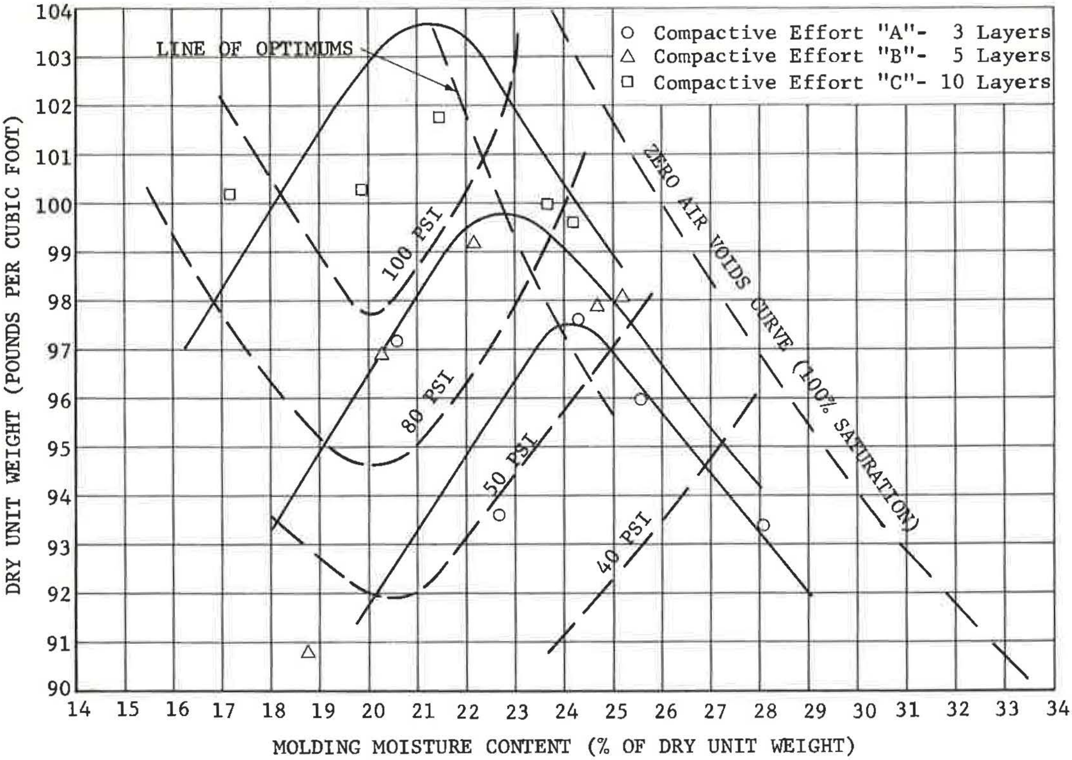


Figure 3. Contours of equal unconfined compressive strength as molded.

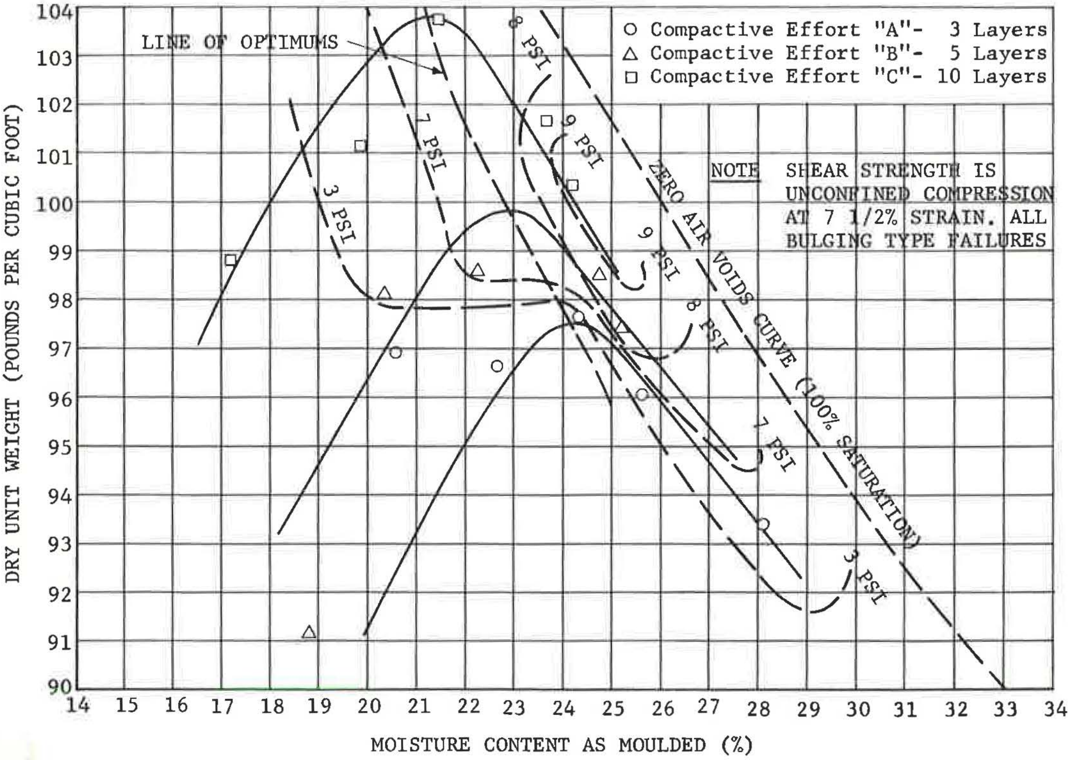


Figure 4. Contours of equal strength after capillarity.

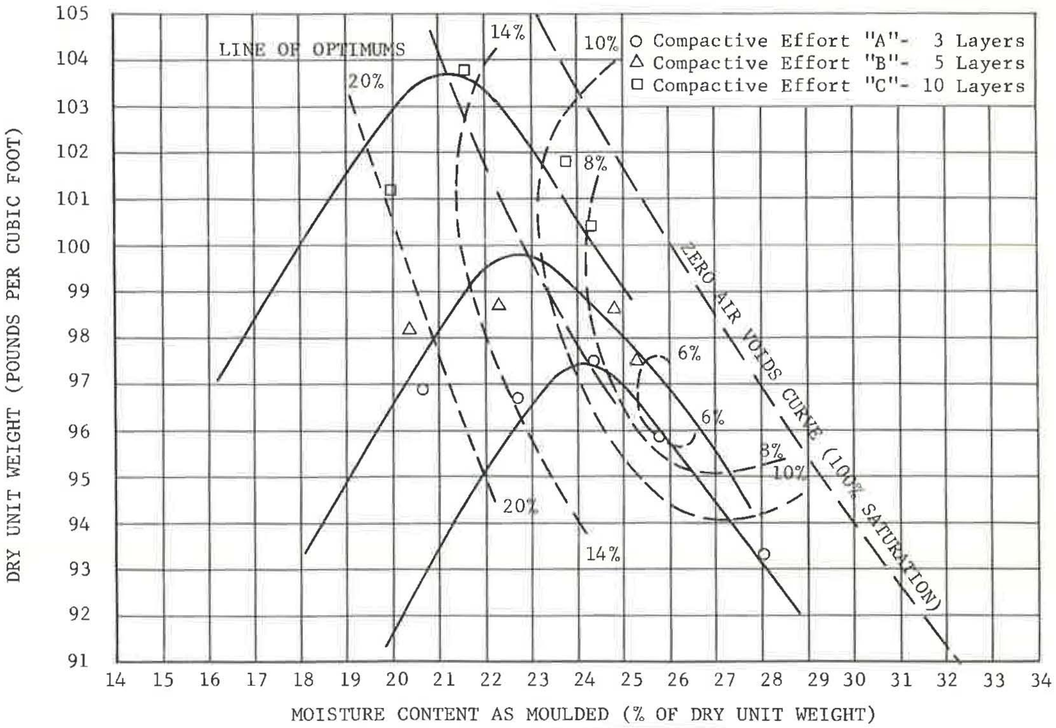


Figure 5. Contours of equal percent volume change after capillarity.

or 2 percent dry of optimum, and the number of roller passes should be as high as economically possible.

MOLDING AND CAPILLARY WETTING

In Figure 4 the unconfined compressive strength after capillary wetting is shown as a function of dry unit weight and moisture content in its as-molded state. Contours of equal strength have been drawn for clarity in presenting the test data. The shear strength has been reduced drastically from the as-molded state and increases as the initial moisture content and compactive effort increases. Figure 5 shows the volume change which occurs when the molded samples are directly exposed to capillarity. Percentage of swell is defined here as the change in volume expressed as a percent of the molded volume. Again, contours of equal swell have been plotted as a means of presenting the test results.

The samples compacted along the line of optimums absorb the least water. The lower the compactive effort, the lower is the amount of water absorption. The percent swell decreased as the compactive effort increased and as the initial moisture content increased.

The results of this series of tests indicate that if this particular material can be prevented from drying out between the time of placement and compaction in the field and when the impervious wearing surface is placed over it, it should be required to be placed as wet (of optimum) as it can be effectively handled. The compactive effort used in placement is not as important as the moisture content being wet of optimum to insure maximum strength and minimum swell after capillary wetting.

MOLDING AND CURING BY AIR DRYING

In Figure 6, the unconfined compressive strength of samples cured by air drying is plotted as a function of unit dry weight and moisture content in their as-molded conditio

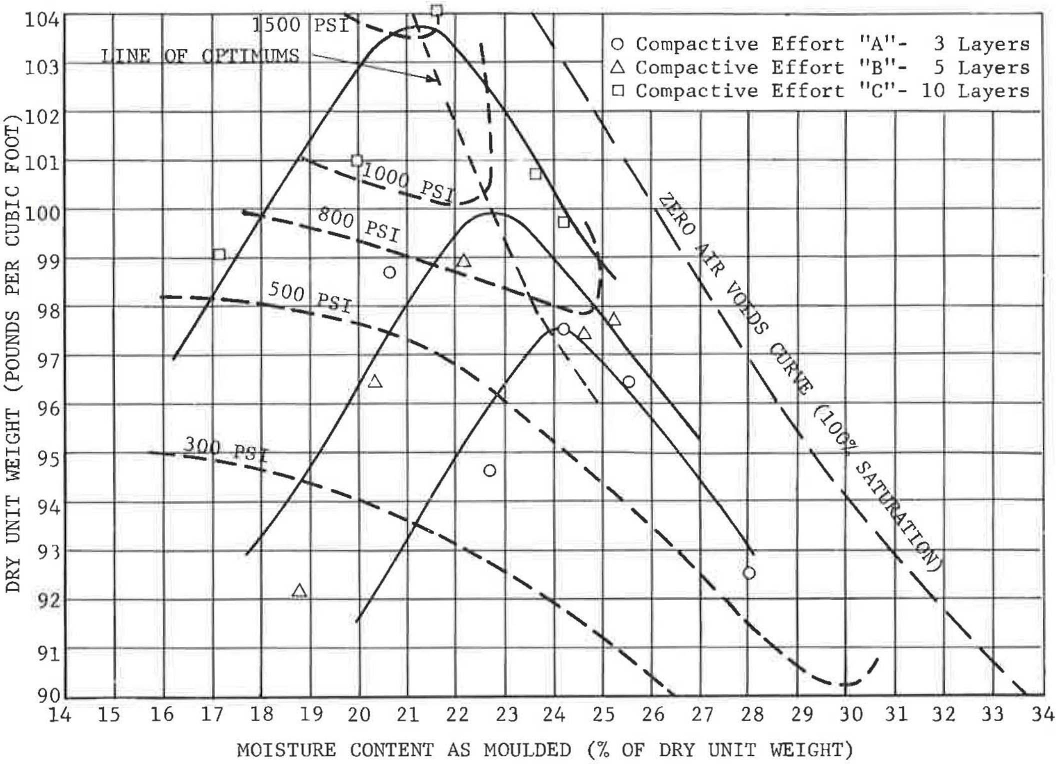


Figure 6. Contours of equal strength after molding and drying.

Generally, the dried strength increases as the compactive effort and initial moisture content increase. The percent volume change (negative) increased as the initial moisture content and compactive effort increased. Figure 7 shows contours of equal skrinkage. Since the samples molded on the wet side of optimum at the highest compactive effort showed extreme distress due to cracking, they were not dried as long as the others and the strengths were not as high. However, from the general trend of test results, it can be inferred that strength after drying is more a function of molding moisture content and drying time than it is of compactive efforts. All of the samples seem to be approaching a constant moisture content, and the samples molded wet of optimum tend to reach higher unit dry weights and unconfined compressive strengths. At the same time, the change in volume (shrinkage) is greatest for these same wet of optimum samples. The shrinkage process adds tremendous cohesive strength to the samples.

If a method could be devised for keeping the material dry after the impervious wearing surface has been placed over the subgrade, the air-dried clay would provide an economical source for load-carrying base material. By using the heaviest economical compactive effort possible on the wet side of optimum molding moisture and then allowing the material to dry out, a material not unlike low-grade concrete can be obtained. The amount of shrinkage would not be detrimental because it could be anticipated. Allowances could be made in the design of bridges, and the wearing surface could be used for a leveling course. To avoid the undesirable cracking associated with those samples molded wet of optimum, careful control of the field operation could be instituted to insure that optimum moisture was used for that particular compactive effort chosen to build the base.

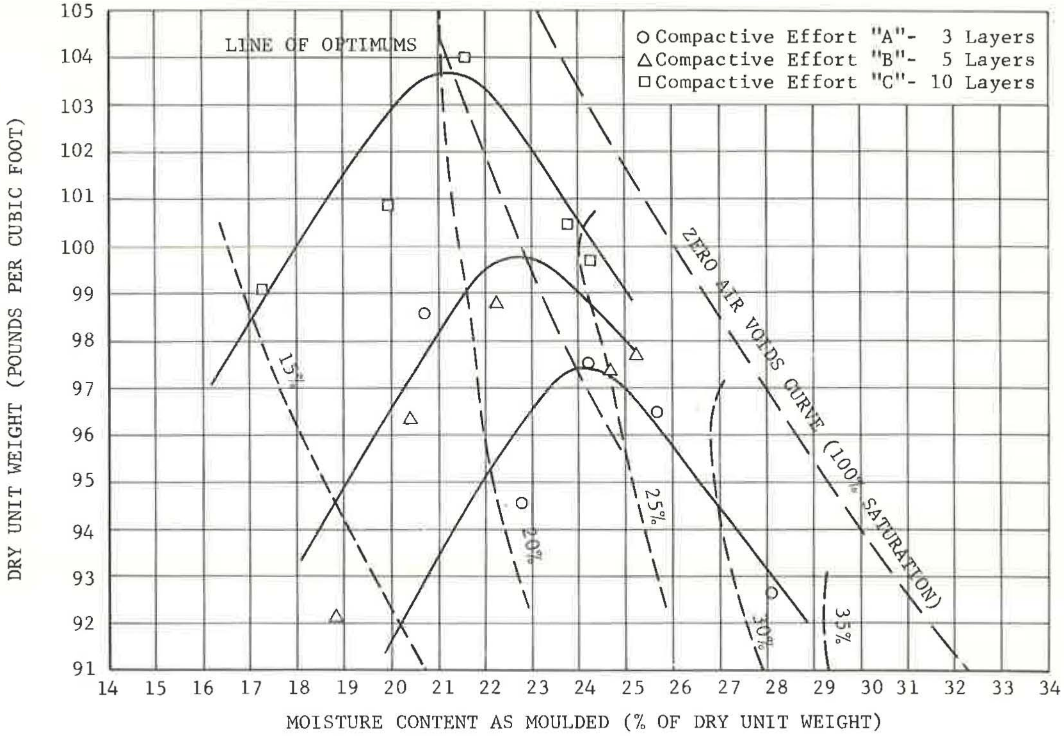


Figure 7. Contours of equal shrinkage after drying (% of molding volume).

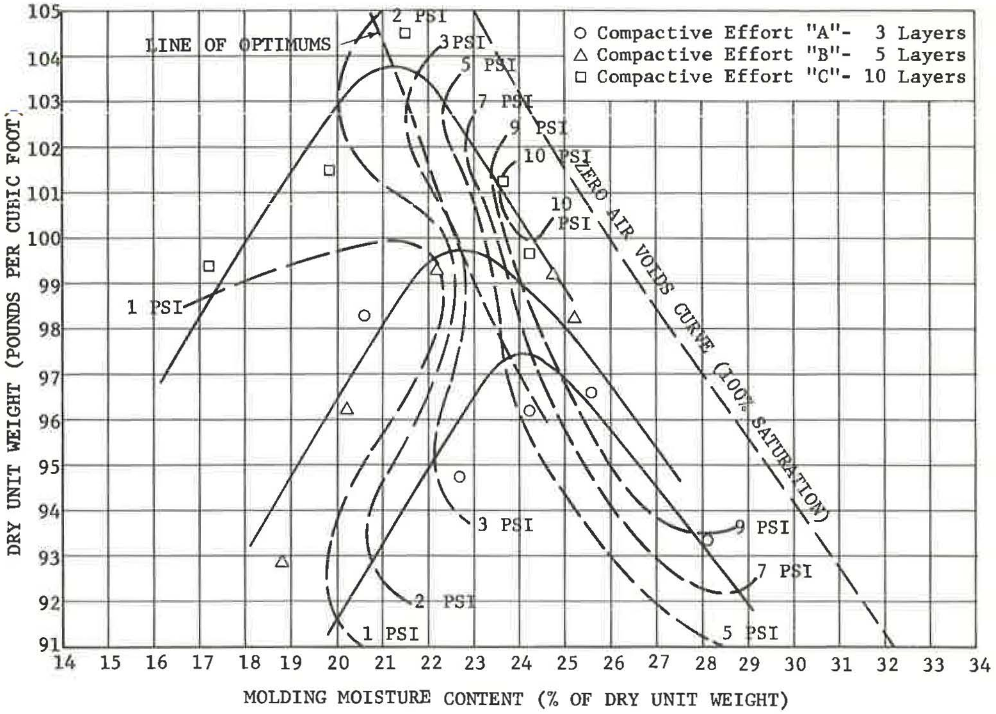
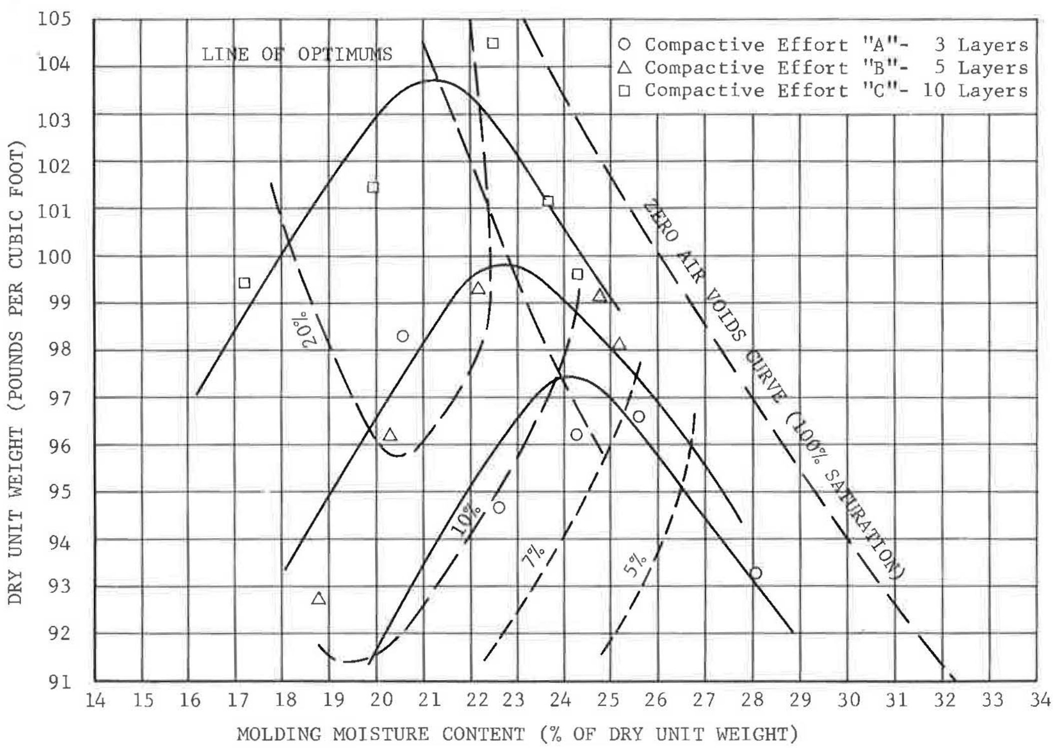


Figure 8. Contours of equal unconfined compression strength after drying and capillarity



gure 9. Contours of equal swell after molding, drying, and capillarity (% of volume change compared to molded volume).

MOLDING, DRYING, AND CAPILLARY WETTING

In an arid region it is likely that the subgrade will shrink by air drying before the base course and wearing surface are installed. Capillary wetting of the subgrade will commence almost immediately, but a long time is required before a constant moisture content is attained.

For these reasons, the test results summarized in Figures 8 and 9 are the most significant for this material. After molding, drying, and capillary wetting, the samples molded wet of optimum displayed the highest strength and the lowest increase in volume for the particular compactive effort used. The lower the compactive effort used, the smaller was the increase in volume after wetting, with little or no decrease in strength.

CONCLUSIONS

The results of the tests suggest a different method for specifying compaction requirements for a clay subgrade in New Mexico. Instead of using only one arbitrary compactive effort, a family of compaction curves should be run in the laboratory. If the subgrade will be permitted to dry out, the laboratory samples should be allowed to dry out and then be subjected to capillary wetting. On the basis of the strength and change in volume after this process, a rational specification can be written.

These tests indicated that for the Fort Wingate clay in the as-constructed condition the maximum dry unit weight should be 101 pcf where the required moisture content would be 24 percent, and that minimum dry unit weight should be 96.5 pcf where the required moisture content would be 25.5 percent. Any satisfactory dry unit weight and moisture content would have to be between these limits and the moisture content

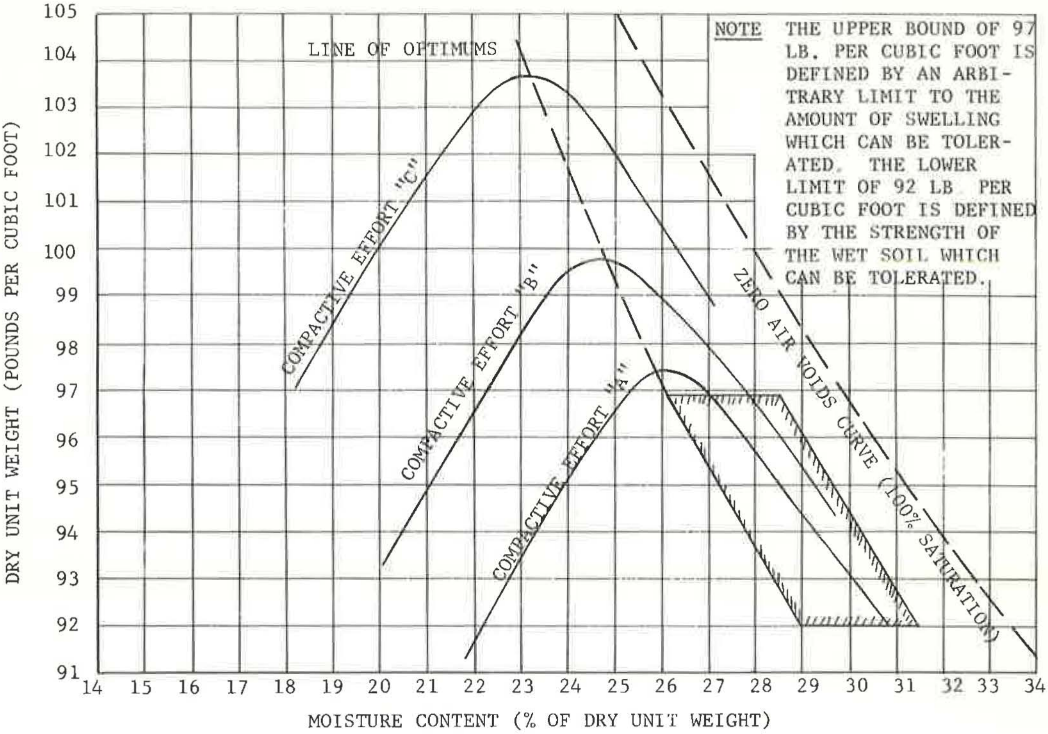


Figure 10. Suggested specification for compaction of Fort Wingate clay to obtain maximum strength and minimum swell.

would have to increase as the dry unit weight decreased. This requirement would limit the volumetric swell to 8 percent and give a minimum shear strength of 8 psi after the subgrade swelled from its as-constructed condition and where it is not allowed to dry out.

If the subgrade is going to be allowed to dry out, the maximum dry unit weight should be 98 pcf where the required moisture content would be 25 percent and the minimum dry unit weight should be 92.5 pcf where the required moisture content would be 29 percent. As before, any acceptable dry unit weight would have to fall between these limits and the moisture content would have to increase as the dry unit weight decreases. This would also give a minimum shear strength of 8 psi and maximum swell of 8 percent from the as-constructed condition. The maximum swell from the dried-out condition would be 30 percent. The general area of acceptable dry unit weights and moisture contents is shown in Figure 10. The subgrade should be tested immediately after rolling and blading is completed and it is primed to prevent further drying out. The roadway section should be designed on the basis of the shear strength of the capillary-wetted subgrade, i. e., by determining the amount of base required to prevent shear failure in the subgrade after it has experienced capillary wetting.

It is recommended that laboratory methods of compaction and capillary wetting simulate more closely what is actually happening in the field. Six-inch layers should be compacted in the laboratory, using molds large enough so that the samples do not expand when extruded. To subject a sample to capillary wetting with lateral and vertical loads similar to those in the field, extrusion is necessary but the difficulties are nearly the same as trying to take an undisturbed sample of soil. The sample is deformed on the sides and expands as the unyielding boundary is removed. The compaction equipment should be applied at the top of the 6-in. layer using some method that would approximate different compaction equipment. The number of applications could be varied to change the compactive effort.

Field research is needed to determine the actual density, moisture content, and shear strength of existing clay subgrades throughout the arid Southwest. This research should be correlated with laboratory and pavement failure studies.

Other arid region clays should be studied and, if possible, some simple test should be devised for field use so that the required dry unit weights and moisture contents could be determined without having to resort to the time-consuming procedure discussed in this paper. In any case, the moisture content must be high, above the line of optimums, and the density must be kept in the lower ranges to obtain reasonable strength and minimum swell after capillary wetting.

Tests conducted at the University of New Mexico also indicate that the Fort Wingate clay can be stabilized with 4 to 8 percent lime and that when 8 percent lime is mixed with this clay and compacted, unconfined compression shear strength is on the order of 150 psi after capillary wetting, and volumetric expansion is very much inhibited. This work should certainly be pursued if clay is to be controlled where roads must be built over them.

Additional research and full-scale tests should be conducted to determine if a subgrade can be kept dry and if the sun can be used to shrink clay for use as a semirigid base material.

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