An Evaluation of Design High-Water Clearances for Pavements

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In this paper is described a study to investigate the effect of capillary water presence on permanent deformation of four common Florida subgrade soils. Physical and engineering properties were first determined, with emphasis on developing soil-water retention characteristics. Repetitive triaxial load tests were then performed on the soils, under several different water conditions. These included at optimum, to represent the as-built condition, and at varied water retention conditions, to represent subgrade conditions in service (i.e., in equilibrium with the designated water table). Deformation characteristics of a subgrade fill, at different water conditions, were related to pavement rutting in accordance with the Shell Oil criteria. When a tolerable permanent deformation was obtained at a specified water condition, the specimen's location on the soil-water retention curve was determined. The height of the most economical subgrade fill could then be fixed.

The presence of excess water in highway pavement systems can accelerate deterioration and destruction of the pavement. Increases in moisture can be caused by the infusion of water from a number of different sources. Results of an investigation of one such source, capillary suction from an underlying water table, are presented.

To prevent capillary water rise into critical areas of a pavement system or to reduce its effects, some state departments of transportation have developed high-water clearance guidelines. In these guidelines the clearance (i.e., a minimum height between a groundwater level and a particular elevation within the pavement system) is specified. The Florida Department of Transportation (FDOT) has such guidelines. They state that the bottom of the pavement base should be located a specific height above a designated high-water level. Details are given in the following table.

Road	*Specification*
Four-lane primary and Interstate	3 ft above 50-year high water
Two-lane primary	2 ft above 50-year high water
Secondary	1 ft above 25-year high water

The policy has been applied uniformly statewide and is intended to satisfy two concerns:

1. That the required compaction and stability be achieved during construction operations and
2. That adequate pavement performance be provided.

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The guidelines, however, do not address the critical factor of subgrade soil type. As a result, there have been locations where the specified clearance appeared excessive for the conditions encountered. However, with no other guidelines to follow, the policy was adhered to. The resulting high fill costs may not be justified. At the other extreme, situations may exist in which the specified clearance may be inadequate. This also leads to eventual waste of funds caused by construction problems or poor pavement performance.

Taking subgrade soil type into account in setting such guidelines requires a determination of which physical and mechanical soil properties influence behavior during construction and under the expected dynamic service loadings. It is also important that the water present in the subgrade be correctly modeled in any laboratory testing (i.e., correct water content and water pressure).

The purpose of the study reported in this paper was to investigate the soil-water retention behavior of four different Florida soils, to determine their deformation characteristics under repetitive loading at different water retention conditions, and to recommend the most economic subgrade height above the water table for each soil.

The research was planned in six phases. These are briefly listed for completeness, though not all are discussed in detail in this paper.

1. A questionnaire was sent to all state departments of transportation to ascertain if they used high-water clearance specifications and, if so, the basis for their criteria.
2. Physical and engineering properties were determined for the four soils. These included grain size distribution, Atterberg limits, specific gravity, permeability, soil mineralogy, density–water content relationships, cohesion, and internal friction angle.
3. Soil-water characteristic curves were obtained for the four soils in two ways: *(a)* using Tempe pressure cells and *(b)* using 4-ft-high compacted soil columns.
4. Repetitive axial loading triaxial tests were performed to obtain deformation characteristics of the four subgrade materials compacted at optimum water content. This represents the as-built pavement condition.
5. Repetitive axial loading triaxial tests were performed to obtain deformation characteristics of the four subgrade materials under different soil-water retention conditions. These represent the subgrade conditions at different depths in service (i.e., in equilibrium with the designated water table).
6. Recommendations for high-water clearances were developed for the four soils based on two procedures: *(a)* an

inspection of the soil-water characteristic curves and the engineering properties and *(b)* use of the Shell Oil criteria for rutting and strains from the laboratory testing and from multilayer elastic analyses.

In this paper, the results from Phase 2 are summarized in a single table. From Phase 3, only the characteristic curves obtained using Tempe cells, which are quite convenient to use, are included. Also, because of length restrictions, the Phase 4 as-built results are not included.

ENGINEERING PROPERTIES OF SOILS TESTED

The four soils tested in the study are representative of the most commonly used fill materials in the state of Florida. They came, respectively, from Polk, Baker, Washington, and Broward counties. Table 1 gives a summary of their physical and engineering properties.

SOIL-WATER RETENTION CHARACTERISTICS

The mechanical behavior of subgrade soils is affected by the presence of water and the development of capillary potential above the water table. It is therefore essential in any study to simulate field conditions for the subgrade soil as it exists, in-service, under the pavement, and in equilibrium with the designated water table. Soil-water characteristic curves provide the necessary parameters to achieve this simulation.

The soil-water retention characteristics of the project soils reported herein were determined using commercially available Tempe pressure cells and a procedure similar to that outlined by Janssen and Dempsey *(1)*. Figure 1 shows retention characteristic curves for all four soils compacted to standard Proctor (T-99). The soils with curves plotting from left to right in this figure have increasing percentages of fines (< 0.074 mm). From the shapes of the curves, those materials susceptible to large changes in the position of the water table are easily recognized.

In this study, only the more critical capillary retention case has been considered. At any elevation above a water table, the water content will be greater in the retention or draining case than in the wetting-up case.

REPETITIVE LOAD TESTING

Specimen Preparation and Conditioning

The water content at any location in a compacted subgrade soil will not remain at the optimum compacted value but will change until it comes into equilibrium with groundwater conditions. The samples for in-service repetitive loading triaxial testing were therefore prepared under optimum conditions, then conditioned to bring them to a desired water content and soil suction state representing some height above the water table.

Samples were compacted in 4-in.-diameter, 8-in.-high lucite molds. To these were fitted a perforated base with filter paper

TABLE 1 ENGINEERING PROPERTIES OF THE FOUR TEST SOILS

Property	Soil Number			
	1	2	3	4
Sand (0.074-4.76 mm)%	95.9	89.5	71.1	5.5
Silt (0.002-0.074 mm)%	4.1	6.5	7.0	73.5
Clay (< 0.002 mm)%	---	4.0	21.9	21.0
Liquid Limit (%)	NP	NP	31	52
Plasticity Index (%)	NP	NP	11	8
AASHTO Classification	A-3	A-2-4	A-2-6	A-5
Unified Classification	SP	SP-SM	SC	MH
Specific Gravity	2.61	2.62	2.68	2.55
Standard Proctor (T-99)				
Optimum Water Content (%)	15.6	13.3	11.8	36.4
Max. Dry Unit Weight (pcf)	102.2	104.9	120.5	73.2
Soil Mineralogy	---	kaolinite chlorite	chlorite	kaolinite montmoril-lonite
Permeability (cm/sec)	7.3×10^{-4}	1.1×10^{-5}	4.8×10^{-7}	6.4×10^{-6}

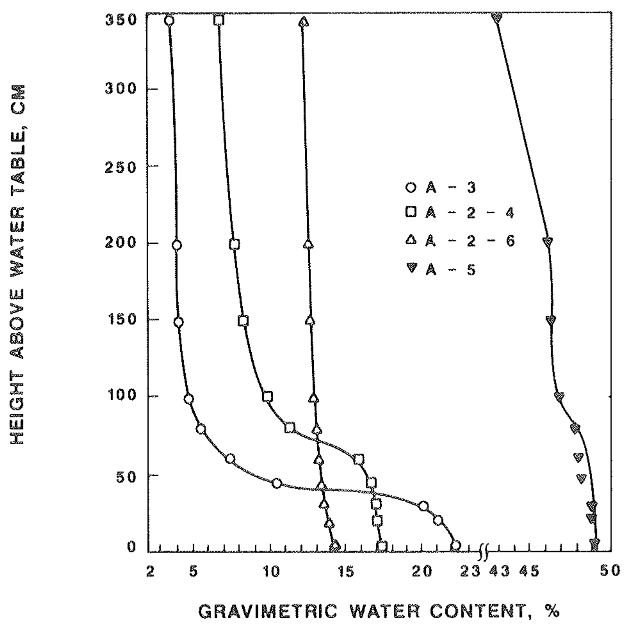

FIGURE 1 Retention characteristic curves for all project soils compacted to standard Proctor.

disc, a top collar, and connecting threaded rods. The assembled mold was then placed in a deep sink and the water level raised to the top of the mold and maintained at that level. Water could enter the specimen only from the bottom. Saturation was assumed when a glaze of water was observed on top of the specimen. The A-3 (sand) took only a few hours to saturate. On the other hand, the A-2-6 (clayey sand) took almost 8 days. After saturation, the water in the sink was allowed to drain slowly to simulate water drawdown in the field. The mold assembly was then lifted out of the sink, dismantled, and the mold weighed. Total unit weight, water content, and degree of saturation could then be calculated.

This provided assurance that the specimen was still saturated. When satisfactory saturation was achieved (S greater than 98 percent) the mold was fitted with a pressure plate (rated at 1 bar), a lucite cup with two drains, a small reservoir, and a water manometer. O-rings and silicon grease were used to seal any gaps between the mold and the lucite cup. The upper end of the mold was covered with a perforated lucite plate to allow air to enter the specimen. Connecting rods were used to hold the cup, mold, and cover together as one unit. This arrangement is essentially a large Tempe cell, except it uses a negative column rather than air pressure to condition the specimen. Figure 2 shows the components of the conditioning cup and Figure 3 a specimen during conditioning. When equilibrium is reached, the specimen is representative of a similar specimen, in the subgrade, at a height above the water table equal to the length of the negative column.

The mold assembly was then taken apart and the wet unit weight and water content of the specimen were determined. A check was then made to determine if the specimen had actually reached the target water content, as obtained from the soil-water characteristic curve. If so, the specimen was ready for repetitive load testing.

Because of the large size of the specimen and the limited distance above the water table to be investigated as a fill height,

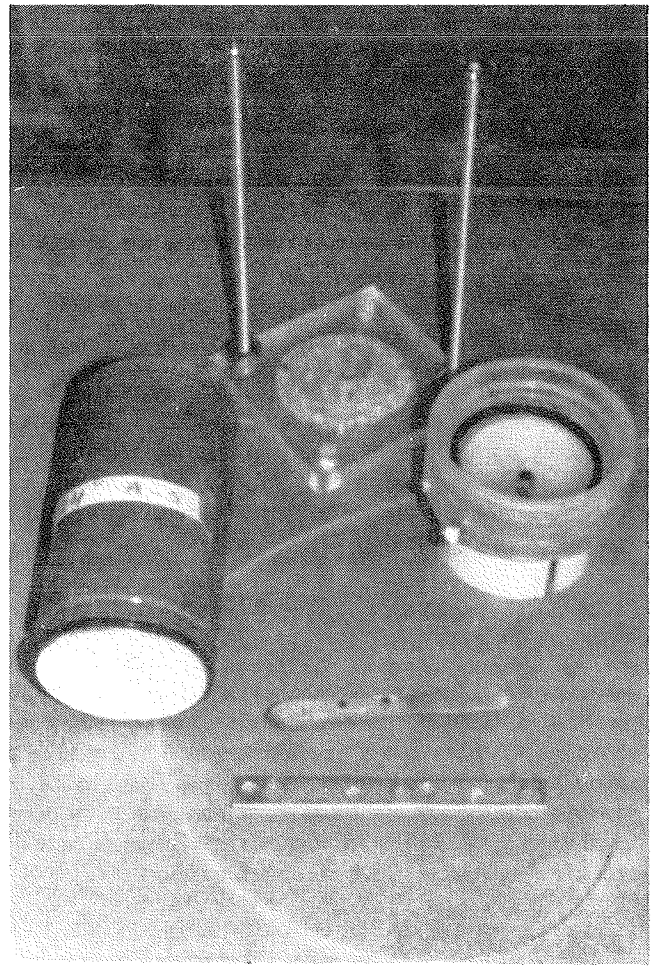

FIGURE 2 Components of the conditioning cup.

attaining the target water content throughout the entire specimen was impractical. For this reason, it was decided that if the water content of the middle 4 in. of the specimen was within 1 percent of the target value, the specimen would be considered acceptable. In some cases, achieving this required considerable time (up to 45 days).

Repetitive Loading Equipment

The repetitive loading equipment consisted of a triaxial chamber capable of accommodating a 4- by 8-in. specimen, vertical and lateral deformation measuring equipment, and a vertical loading source. The external loading source was a closed-loop electrohydraulic system manufactured by MTS Systems Corporation. An electronic load cell measured the axial forces. The axial and radial deformation measurements were made using two pairs of linear variable differential transformers (LVDTs). These were mounted on a pair of expandable clamps that contacted the specimen through four wide feet on each clamp. Air was used as the chamber fluid and was monitored with conventional pressure gauges. Signal excitation, conditioning, and recording equipment provided for simultaneous recording of the axial loads and deformations. The LVDTs were wired so that the average signal from each pair was recorded. Figure 4 shows an overall view of the equipment used.

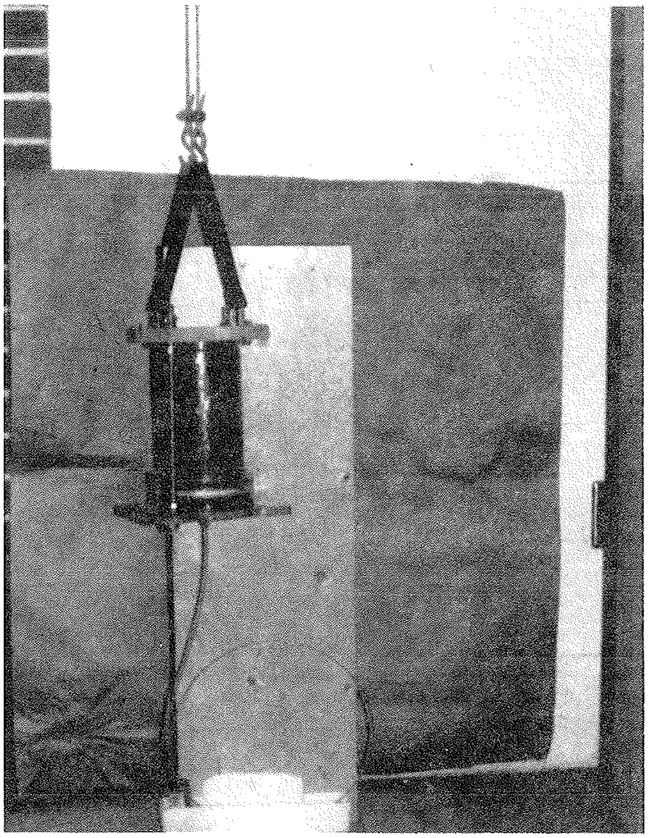

FIGURE 3 Specimen during conditioning.

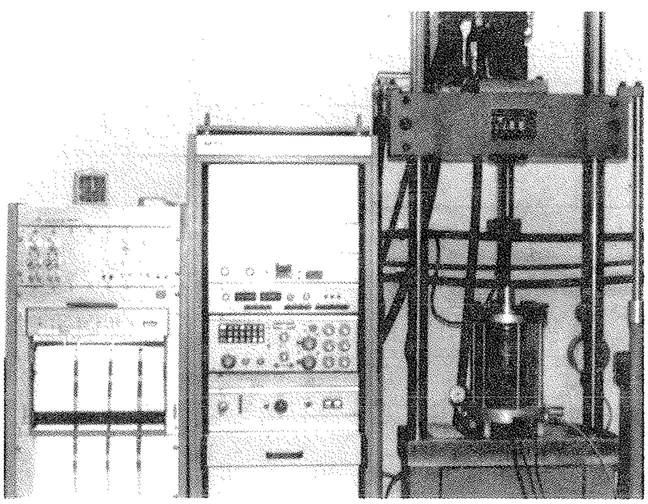

FIGURE 4 Overall view of the repetitive loading test equipment.

Testing Procedure

The objective of the repetitive load testing was to characterize the resilient and permanent strains of the project soils at different water retention conditions. The condition specimen was extruded from its mold and assembled in the triaxial chamber with top and bottom porous stones, surrounding rubber membrane, and the horizontal and vertical LVDT clamps at 2- and 6-in. heights. A confining pressure of 2 psi was first applied for 30 min under drained conditions.

The MTS controls were set to give a 0.1 sec load on and a 0.9 sec load off. The pulse wave was haversine. Because the specimen diameter and the stress desired were known, the load could be calculated and the controls set accordingly. The confining pressure was maintained at 2 psi in all tests. Dynamic conditioning of the specimen was performed to eliminate the end imperfection of the specimen, to allow for better seating of the porous stones, and to eliminate the effects of the interval between compaction and loading. This dynamic conditioning consisted of first applying 200 load repetitions of a 2-psi deviator stress (σ_1 = 4 psi and σ_3 = 2 psi). The axial load was then incremented by 2 psi after each 200 repetitions until a total axial load of 8 psi was applied, (deviator stress σ_d = 6 psi). Specimen testing was started at the end of 600 repetitions of conditioning with the same stress as the last 200 repetitions. The stress level of σ_d = 6 psi and σ_3 = 2 psi was considered representative of the stresses encountered in the field in the subgrade layer. All specimens were tested for 10,000 repetitions. Test data were recorded at or near the following repetition levels: 1; 10; 100; 200; 400; 600; 800; 1,000; then every 1,000 until the termination of the test. Test data monitored included axial load, axial deformation, and radial deformation. These were recorded on a strip chart recorder.

Testing Program

Table 2 gives the different water retention conditions tested. These were selected from the water retention curves of Figure 1 to model conditions in the subgrade at different heights above the water table. Average specimen dry densities were 103.2 pcf for the A-3, 107.9 pcf for the A-2-4, 119.5 pcf for the A-2-6, and 72.1 pcf for the A-5. These values are the averages of three specimens in each condition.

EXPERIMENTAL RESULTS

Results from the conditioned specimen repetitive load testing of the four subgrade soils were analyzed in terms of the permanent and resilient strains (ε_p^a and ε_r^a) and the resilient modulus (M_R).

The A-3 soil was tested by repetitive loading under three different water retention conditions (Table 2). Figure 5 shows a cumulative plot of axial permanent strain (ε_p^a) versus number of stress applications (N) for the three water retention conditions. The curves stack: the one representing 24 in. is at the bottom; the one representing 18 in. is in the middle; and the one representing 15 in. is at the top. For a certain number of stress applications, the bottom curve yields the lowest axial permanent deformation and the top curve the highest. A power function, of the form

$$\varepsilon_p^a = AN^B$$

where

ε_p^a = accumulated axial permanent strain;
N = number of stress applications; and
A, B = constants (which would represent intercept and slope terms, respectively, on a log-log plot)

TABLE 2 TEST PROGRAM OF PROJECT SOILS UNDER DIFFERENT WATER RETENTION CONDITIONS

Height Above Water Table in inches	Soil Type			
	A-3	A-2-4	A-2-6	A-5
	Water Content Percentage			
15	13.24			
18	10.53			
24	8.10			
30		11.70		
36		10.50		
48		8.70		
0			12.20	
36				44.40

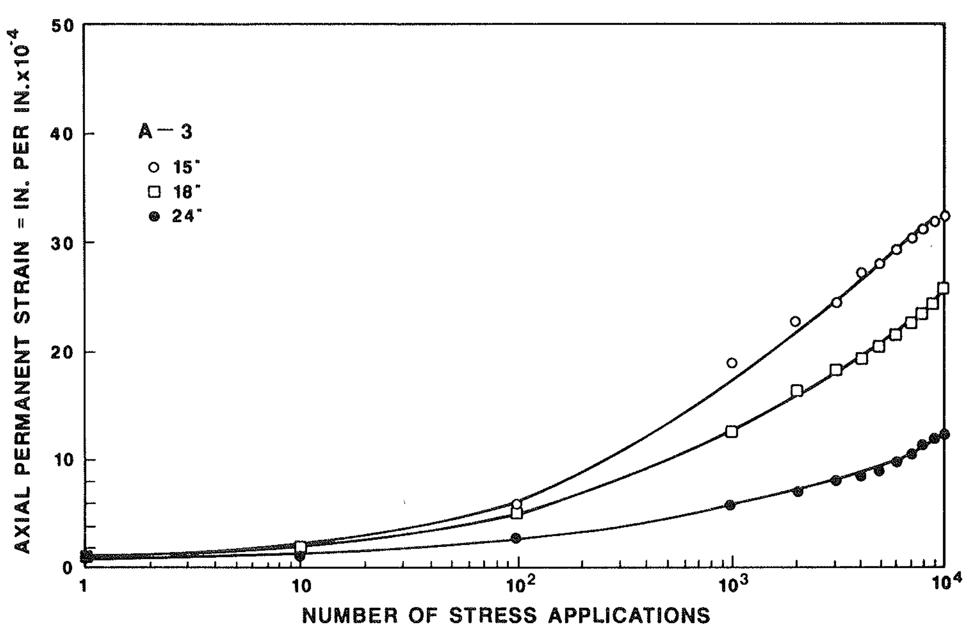

FIGURE 5 Accumulated axial permanent strain versus number of stress applications for A-3 soil at different water retention conditions.

was found to fit all the data points. Such a function was also reported by Monismith et al. *(2)* and was verified for up to 100,000 stress applications. The data are presented in semilog format to better show the change in permanent strain with the number of stress applications. These results are in general agreement with those of Shackel *(3)*, showing that the cumulative permanent (axial) strain decreases rapidly with increasing suction.

The A-2-4 soil was also tested under three different levels of water retention. Water contents chosen were 11.70, 10.50, and 8.7 percent, representing 30, 36, and 48 in. above the water table. Figure 6 shows the plots of ε_p^a versus N. Again, as expected, the plot representing the greatest distance, 48 in., was located at the bottom of the figure; that representing 36 in. was in the middle; and the 30-in. plot was on top. The A-2-4 soil showed behavior quite similar to that of the A-3 soil. Power functions again can be used to fit the data.

The A-2-6 and A-5 soils were each tested at only one selected water retention level. The A-2-6 specimen was prepared by soaking in water for 8 days. This procedure led to a water content of only 12.2 percent. This was considered as saturated as this specimen could be. The specimen was never placed under any capillary tension. The condition therefore represents the worst that might be encountered in the field.

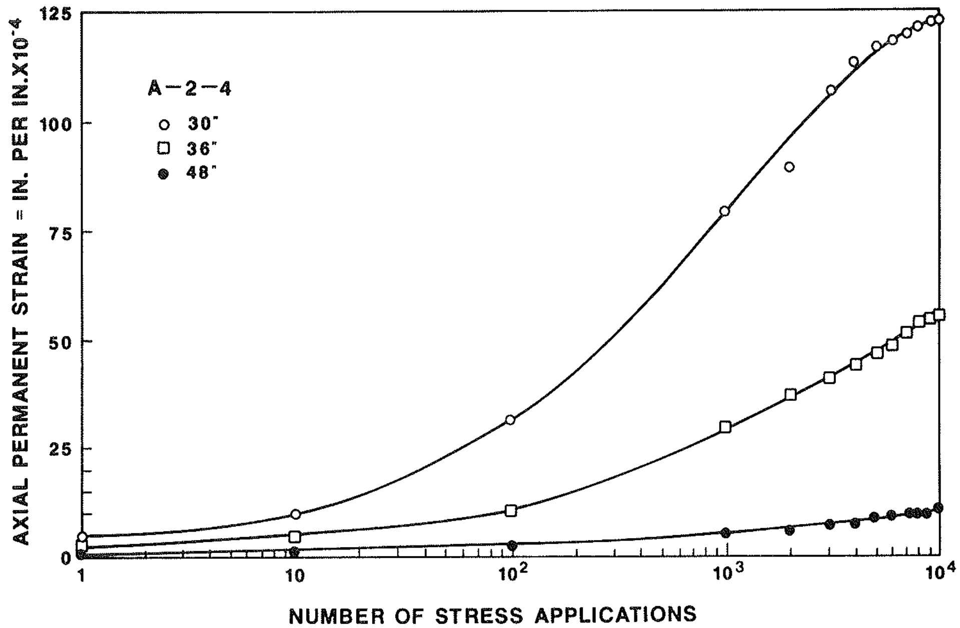

FIGURE 6 Accumulated axial permanent strain versus number of stress applications for A-2-4 soil at different water retention conditions.

The A-5 soil was placed under a capillary tension to represent a height of 36 in. above the water table. Its water content was 44.4 percent. Figures 7 and 8 show the plots of ε_p^a versus N. A power function was found to fit the data in the first stages up to 7,000 and 5,000 applications for the A-2-6 and A-5 soils, respectively. The second stage for both soils was a plateau where no increase in permanent strain was observed.

Table 3 includes a summary of M_R-values, the correlation equations and their coefficients, and the R^2 values for all four project soils at their different water retention conditions.

APPLICATION OF TEST RESULTS

The results obtained from both the engineering properties tests and the repeated load tests can be used in the following ways:

1. They will provide a data base on the essential engineering and physical properties of four common subgrade fill materials available in the state of Florida. This should help in making an economical decision about the selection of fill materials and the certification of borrow pits.

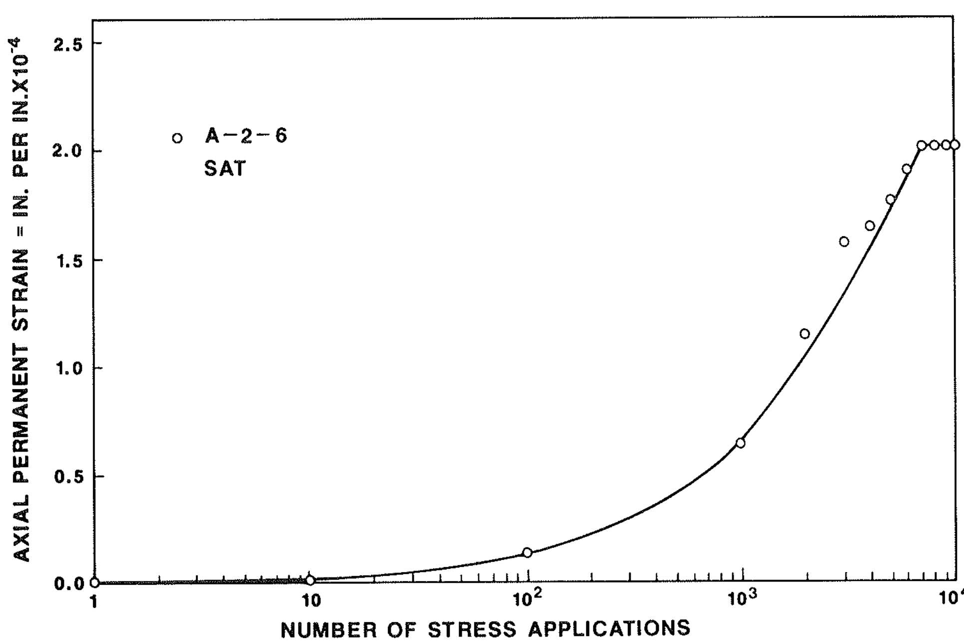

FIGURE 7 Accumulated axial permanent strain versus number of stress applications for A-2-6 soil at a single water retention condition.

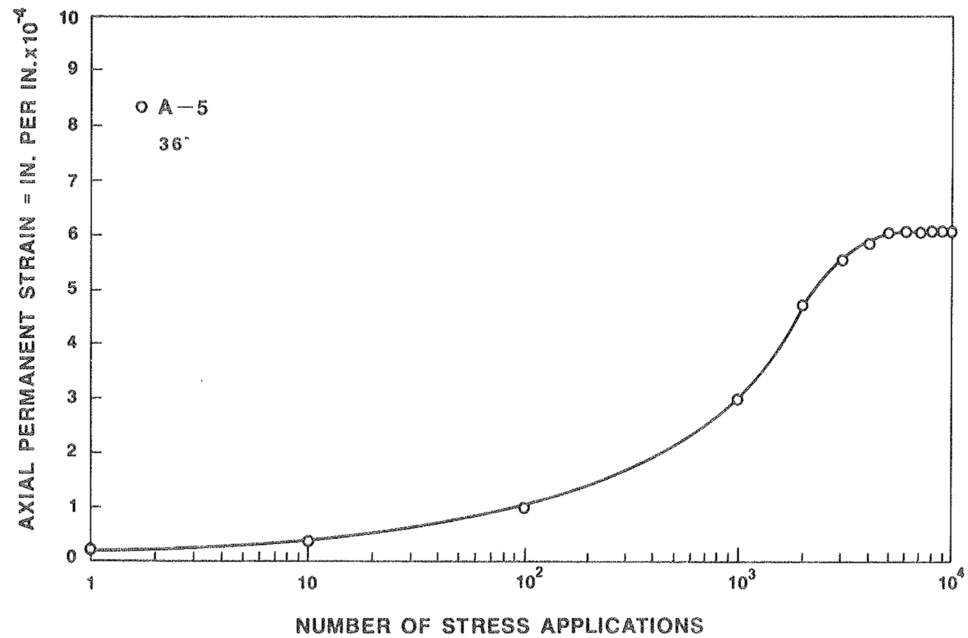

FIGURE 8 Accumulated axial permanent strain versus number of stress applications for A-5 soil at a single water retention condition.

2. The soil-water characteristic curves provide a realistic simulation of the water retention in a subgrade. Similar distributions have been found in field investigations reported by Kersten *(4)*, Russam *(5)*, and Janssen and Dempsey *(1)*. Instead of assuming full saturation, it is appropriate to estimate subgrade strength on the basis of such soil-water characteristic curves. This should be superior to simply assuming a regional (environmental) factor (1 for Florida) as is done in part of the AASHTO design procedures. From the soil-water characteristic curves, it can be seen that for a subgrade fill at a height that falls within the capillary fringe (almost fully saturated), water will have a detrimental effect on strength. This has been reported by Barber and Sawyer *(6)*. The minimum height of subgrade fill should therefore be greater than the height of the capillary fringe. Such a fill benefits from the strengthened effect caused by capillary suction and negative pore water pressures. This was demonstrated during repetitive load testing. Figures 5 and 6 show that the greatest axial permanent deformations occurred in the specimen representing the top of the capillary fringe, 15 in. in the A-3 soil and 30 in. in the A-2-4

TABLE 3 SUMMARY OF PREDICTION EQUATIONS AND M_R-VALUES FOR ALL PROJECT SOILS AT DIFFERENT WATER RETENTION CONDITIONS

Soil Type	Water Retention Condition %	Range of M_R psi	M_R at N = 1,000 psi	Number of Stress Applications N	Type of Function	Intercept A	Slope B	R^2
A-3	13.50	27,429-35,556	32,000	1-10,000	power	0.89	0.41	0.98
	10.53	33,103-56,471	35,553	1-10,000	power	0.90	0.37	1.00
	8.10	36,923-43,636	38,400	1-10,000	power	0.72	0.30	1.00
A-2-4	11.70	23,577-37,723	27,738	1-10,000	power	5.18	0.37	0.97
	10.50	26,667-35,556	28,235	1-10,000	power	2.18	0.36	0.99
	8.70	24,000-32,000	30,000	1-10,000	power	0.12	0.49	0.98
A-2-6	12.20	43,478-48485	43,478	1- 7,000	power	5.43×10^{-3}	0.68	0.97
		48,000	--	7,000-10,000	linear-flat	2.00	0	1.00
A-5	44.40	10,101-11,173	10,118	1-5,000	power	0.16	0.43	0.99
		11,152	--	5,000-10,000	linear-flat	6.06	0	1.00

soil. For the specimens representing heights above the capillary fringe, the axial permanent strains are greatly reduced.

A-3 subgrade fill could be built to a minimum height of 15 in. (see Figure 1). It is, however, recommended that A-3 subgrade fills be built up to 24 in. This provides a safety margin, introduced because of the soil's high permeability and the ease with which it might be saturated from some other moisture source.

For the A-2-4 soil, the minimum height is 30 in. A height of 36 in. is recommended, and this height is supported by the repetitive load testing results shown in Figure 6. A 48-in. height would not be justified.

For the A-2-6 soil, there is no distinguishing capillary fringe. Figure 1 shows a gradual uniform decrease in water content with height above the water table. The significant property of this soil is its well-graded nature and consequently its low void ratio. Because of this, the structure is strong even when the soil has been under water for 1 week. For the A-2-6 soil, a 12-in. height is suggested. Figure 7 shows the quite low permanent deformation and high resilient modulus of the A-2-6 soil.

The shape of the soil-water characteristic curve for the A-5 soil was found to be quite dependent on the method of compaction and voids formation (Figure 8). It is therefore difficult to assign a conclusive capillary fringe height. The soil remained near saturation up to 200 cm (6.5 ft) with the curves showing a break at 91 cm (3-ft). The water content loss at this break was approximately 2 percent. A specimen was saturated and placed under a 91-cm (3-ft) negative column. The water content obtained was 44.4 percent. This specimen was then tested under repetitive loading. Its resilient strain was high compared with that of the other three soils. In addition, swelling was observed at the end of the saturation stage. Such serious drawbacks must be carefully weighed against economics before it is decided to use the A-5 soil as subgrade fill. However, it is recognized that in some circumstances it will be the only material available within an economical hauling distance. In these cases, a height between 4 and 6 ft (5 ft average) is recommended as a reasonable fill height.

The recommendations in this section pertain only to the soils tested in this project. The capillary fringes reported were based on the draining case (retention condition) and a soil structure achieved by the mechanical compaction method. Figure 9 shows the recommended heights of subgrade fill for the project soils, based on the retention case capillary fringes.

3. The resilient modulus, obtained from laboratory testing of the project soils under a variety of water retention conditions, can be used as input in a multilayer elastic analysis. BISAR (BItumen Structures Analysis in Roads) is a general-purpose program for computing stresses, strains, and displacements in elastic multilayered systems subjected to a uniform load over a circular surface area. BISAR was introduced in 1972 by Koninlijke/Shell Laboratorium, Amsterdam *(7)*. Obtaining the stresses and strains from such an analysis will allow a comparison to be made with the Shell Oil Company criteria (Shell criteria) for limiting subgrade strain.

The following parameters were used in a series of BISAR program runs:

- Wheel load = 9,000 lb (18,000-lb axle load);
- Tire pressure = 100 psi;
- Radius of circular surface area = 5.35 in.;
- Poisson's ratio = 0.35;
- M_R, asphalt concrete (3 in.) = 171,000 psi;
- M_R, lime rock base (10 in.) = 84,000 psi; and
- M_R, stabilized subgrade (12 in.) = 60,000 psi.

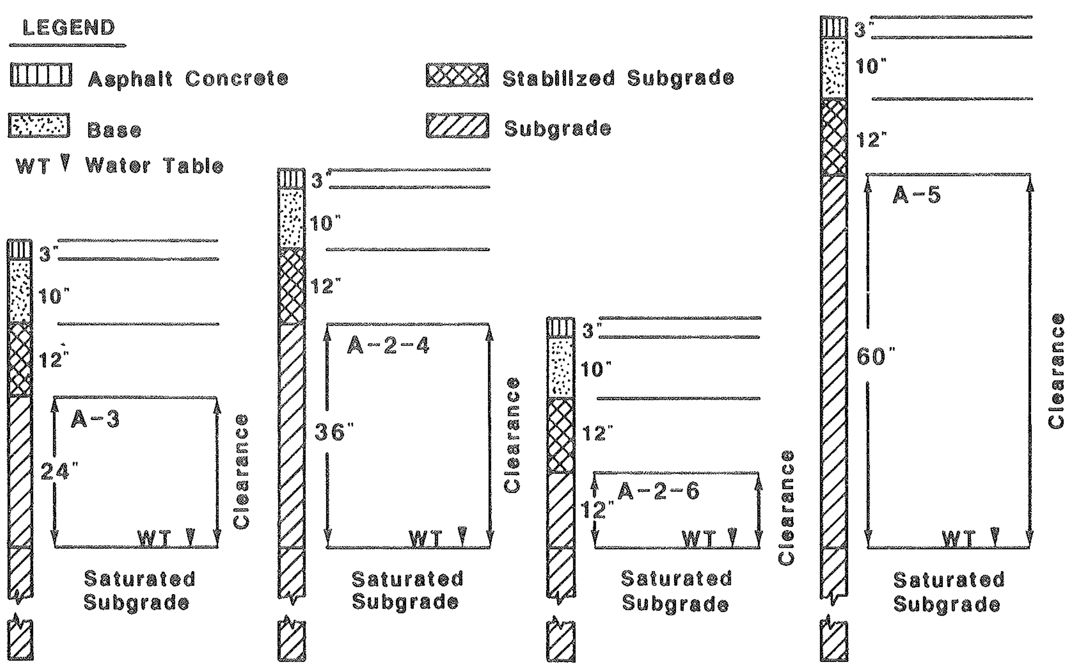

FIGURE 9 Recommended subgrade clearance heights for project soils based on capillary fringe (retention case).

Resilient moduli for the subgrade layers depend on the material and on its location above the water table. Table 4 gives values for the four project soils at 10,000 repetitions and the corresponding heights above the water table. The final layer, below the water table, was given a modulus value of 10,000 psi. This value was chosen because the weakest material at saturation, the A-5, had an M_R-value of 11,152 psi.

These parameters were also used as input in BISAR, with an overload of 30-kip axle load and 125-psi tire pressure (radius = 6.18 in.). Table 5 gives a summary of the strains at the top of the subgrade based on laboratory tests and BISAR's output at 18 and 30 kips. Table 6 gives the Shell criteria (i.e., limiting subgrade compressive strain values corresponding to different numbers of load applications). These criteria were established

TABLE 4 SUBGRADE RESILIENT MODULI USED AS INPUT IN BISAR PROGRAMS

Height Above Water Table in inches	Soil Type			
	A-3	A-2-4	A-2-6	A-5
	M_R (Resilient Modulus, psi) at 10,000 Rep.			
15	28,235			
18	34,286			
24	40,000			
30		24,666		
36		30,968		
48		32,000		
0			48,000	
36				11,152

TABLE 5 SUMMARY OF STRAINS AT TOP OF SUBGRADE FROM LABORATORY TESTS AND FROM BISAR'S OUTPUT AT 18 AND 30 KIPS

Height Above Water Table	Soil Type											
	A-3			A-2-4			A-2-6			A-5		
in inches	Lab.	18k	30k	Lab.	18k	30k	Lab.	18k	30k	Lab.	18k	30k
15	2.13	1.55	2.54									
18	1.75	1.38	2.25									
24	1.50	1.25	2.05									
30				2.43	1.70	2.83						
36				1.94	1.50	2.47						
48				1.88	1.45	2.44						
0							1.25	1.07	1.75			
36										5.38	2.61	4.28

Note: All strain values are in in/in x 10^{-4}

TABLE 6 SHELL CRITERIA—LIMITING SUBGRADE COMPRESSIVE STRAIN VALUES CORRESPONDING TO DIFFERENT LOAD APPLICATIONS

Load Repetitions	10^5	10^6	10^7	10^8
Axial Compressive strain in/in x 10^{-4}	10.5	6.5	4.2	2.6

by the Shell Oil Company in 1962 and were documented by Dormon and Metcalf *(8)*. The Shell criteria were developed from elastic analyses of pavements designed according to the California bearing ratio (CBR) procedure and from pavements in the AASHO Road Test. The Shell criteria ensure that permanent deformations in the subgrade will not lead to excessive rutting at the pavement surface. If the actual performance results from the AASHO Road Test are considered in terms of rut depth, the Shell criteria in Table 6 may be thought to be associated with an ultimate rut depth on the order of 3/4 in.

The strain corresponding to 10^8 load applications in the Shell criteria was selected for comparison with the strains obtained from the laboratory tests and from the BISAR output for the 18- and 30-kip loads. The 10^8 load applications for a 20-year service life were recommended by the FDOT for the heavy traffic on an Interstate highway. From Table 6 a value of 2.6×10^4 in./in. strain is found to correspond to 10^8 load applications.

The comparisons show that, for the laboratory strains, all tested subgrade heights would qualify as adequate, except the A-5 at 36 in. For the strains output by BISAR for an 18-kip axle load, all heights qualify as adequate subgrade heights. For the BISAR 30-kip axle load, all heights qualify as adequate except the A-2-4 at 30 in. and the A-5 at 36 in. The BISAR program takes into account the relative stiffnesses of the pavement layers (i.e., the asphalt concrete, base, and stabilized subgrade). This leads to a reduction in the stresses and strains on top of the subgrade compared with the Boussinesq solution and the results of laboratory tests. The BISAR solution with the 30-kip axle load resulted in higher strains than did the laboratory testing, except in the A-5 soil. Because of this and to be on the safe side, the overloads have been considered in the comparisons to qualify certain subgrade heights above the water table. The comparisons were based on 10^8 load applications. Note that if 10^7 load applications were considered, the strain criterion would be 4.2×10^{-4} in./in. (from Table 6), and all heights of subgrade fill above the water table would qualify as adequate except the A-5. For 10^6 applications, the A-5 with a height of 36 in. would also be adequate. The Shell criterion strain for 10^6 load applications is 6.5×10^{-4} in./in. This strain level is about 30 percent higher than the strain for the A-5 soil under a 30-kip axle load. The 30 percent higher strain could be considered a safety margin for this particular condition. Figure 10 shows the recommended subgrade clearance heights above the water table, based on the overload of 30 kips for the project soils.

This analysis agrees well with that done using capillary fringe heights.

CONCLUSIONS

1. Soil gradation, the percent passing the No. 200 sieve, and the mineralogy of the subgrade soil influence soil-water retention characteristics to a great extent (Figure 1).

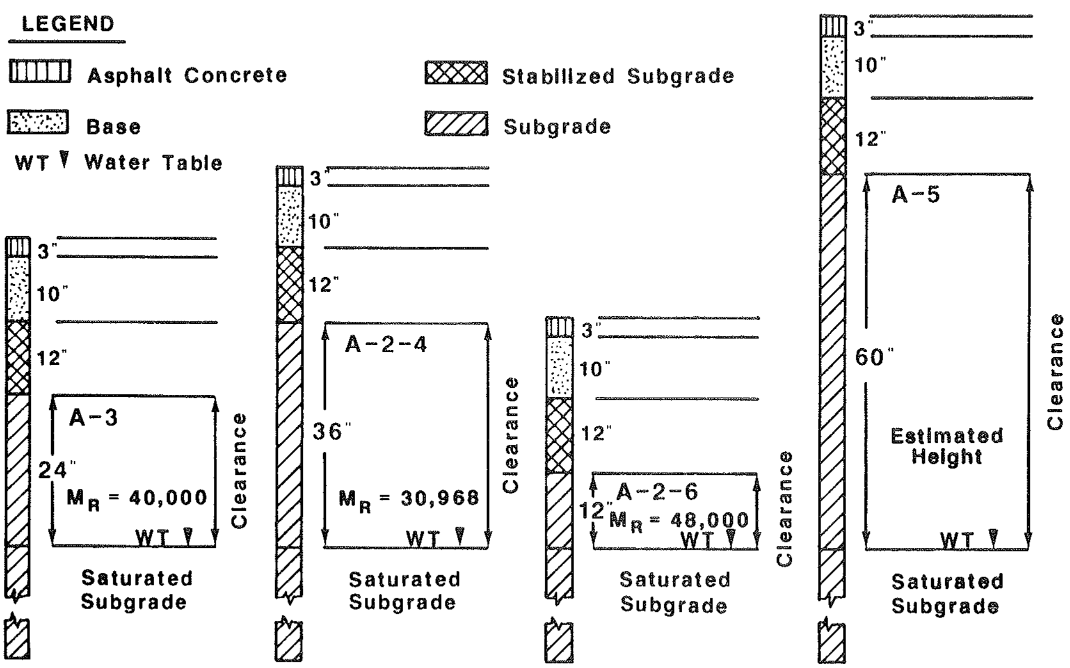

FIGURE 10 Recommended subgrade clearance heights based on a 30-kip axle load and 10^8 load applications for the project soils.

2. At different heights above the water table, the subgrade fill possesses different deformation characteristics. The greater this height, the stronger the fill (Figures 5 and 6).

3. The deformation characteristics of the subgrade soil (i.e., the plot of accumulated axial permanent strain versus number of stress applications at different water retention conditions) can be represented by a power function of the form

$$\varepsilon_p^a = AN^B$$

4. As a prospective subgrade fill, the A-2-6 soil tested in this research appears to be the best of the four project soils.

5. The A-5 soil has a tendency to swell because of its montmorillonite content. It also possesses very high resilient strain.

6. On the basis of the soil-water characteristics capillary fringe, an analysis using results from repetitive load testing, the BISAR computer program, and the Shell criteria, a subgrade fill of 24 in. is adequate for the A-3 soil, 36 in. is adequate for the A-2-4, and 12 in. is adequate for the A-2-6. If the A-5 soil must be used, a careful analysis should be undertaken. A fill thickness in the range of 4 to 6 ft is probably adequate for the A-5 soil.

7. The gradation of each soil can be related to its compaction characteristics. The well-graded A-2-6 soil showed the highest dry density at optimum. That in turn was reflected in the response of the soil during repeated load testing, when it experienced quite small permanent strain. On the other hand, the A-2-4 soil experienced high permanent strain and high elastic strain due to its uniform gradation and poor drainability.

8. Soil type is an important factor and should be considered in current guidelines for evaluating high-water clearances in pavements. This is based on the variation in deformation characteristics found in the different soils.

Note: The research study on which this paper is based is reported in detail by Elfino *(9)* and Davidson et al. *(10)*.

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