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ENVIRONMENTAL FACTORS AFFECTING THE STRENGTH OF SUBGRADES

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U.S. Public Roads AdministrationSEASONAL CHANGES AFFECT MOISTURE-DENSITY-STRENGTH RELATIONS

Factors which cause changes in the moisture content, density, and strength of subgrade soils in-place, especially in areas where freezing and thawing temperatures occur, include the texture and structure of the soil, the position of the water table, and variations in rainfall and temperature.

As a general rule, the moisture contents will be higher in fine-grained soils such as silts, silty clays, and laminated fine sands with silty clays, and will be the lower in the more granular soils. The strength of soils varies inversely as the moisture content for a soil having a given structure but inasmuch as soil structure is a variable depending upon the method of compaction and the time factor, a definite relation between strength and moisture content may be difficult to establish for the variety of subgrade conditions found in the field.

Recent work by the U.S. Engineer Department 1) shows that different methods of compacting soils at the same moisture content and to the same density affects the strength of the soil as measured by the CBR test. This appears particularly significant since the strength of the soils was determined after the samples had been allowed to soak and take up additional soil moisture. Similar variations in the moisture-density-strength relations probably occur in subgrades under pavements since different methods of manipulation and compaction used in the field will develop different soil structures. Thus, the strength of soils determined under laboratory conditions may not agree with in-place strength data obtained by testing subgrades constructed from similar soils.

The movement and accumulation of water in subgrades vary with temperature and rainfall and are consequently affected by seasonal climatic changes.

The test data shown in table 1 were obtained from a series of undisturbed soil samples taken beneath an experimental test pavement located near Washington, D.C. The subgrade soil was a plastic clay having a liquid limit of 51 and a plasticity index of 24. Prior to the construction of the pavement, the surface soil was removed and the underlying soil was manipulated to a 9-inch depth and compacted to standard A.A.S.H.O. density at optimum moisture content. Adequate drainage was provided to minimize any concentration of surface water in the vicinity of the test pavement so that the subgrade moisture content would not be affected by poor drainage conditions.

A study of these data indicates the seasonal effect of climatic factors (rainfall and temperature) upon the moisture-density-strength relations over a period of approximately 9 months. The moisture content increased from optimum moisture content to slightly above the plastic limit from the summer of 1945 to the spring of 1946. The dry density decreased with the increase in moisture content during the same period. The strength of the subgrade as measured by the maximum vertical minus lateral pressure in the triaxial compression test appears to follow the seasonal cycle of climatic chan-

ges, being highest during the summer months and lowest during the fall, spring, and winter months.

This test pavement was not subjected to the action of traffic and it is not known whether these moisture-density-strength relations would have been appreciably altered by the compactive effect of traffic. However, an investigation 2) of subgrade moisture occurring beneath airport pavements in United States indicates that the average moisture content and percent saturation of clay subgrade soils are in substantial agreement with the data obtained from the test pavement. No comparisons could be made between seasonal variations in strength of airport subgrades and those observed in the test pavement as the strength of the soil was not considered a part of the airport investigation, but it is reasonable to believe that similar seasonal changes are likely to occur.

Although these data only show trends, it raises a question of whether it is desirable to compact soils at higher densities such as obtained by the modified A.A.S.H.O. method for subgrades beneath highway pavements. It appears that subgrade density may be lowered to less than standard A.A.S.H.O. requirements by the action of climatic factors.

These data suggest the need for additional field investigations to obtain similar information for different types of subgrade soils under a wider range of climatic factors. Several different thicknesses of pavement should be included in the field study to determine the effect of insulation courses on the moisture-density-strength data.

PAVEMENT PERFORMANCE IS RELATED TO ENVIRONMENTAL FACTORS

In the correlation of soils with pavement behavior, it has been established that the strength of subgrades is related to the environmental factors of climate and relief. For similar conditions of traffic and pavement design, the pumping of concrete pavement joints, the alligator cracking of bituminous surfaces, frost heaves, frost boils and general spring breakup conditions are manifestations of the effect of these factors on the strength of subgrade soils.

A recent survey of conditions of concrete pavement in Tennessee 3) indicates that environmental factors could be used to differentiate between pumping and nonpumping pavement joints even though the physical test constants of the soil could not be used to explain their behavior in the roads built over "loess" subgrade soils. It was found that the soil profile characteristics of the native soils occurring within the road right-of-way could be used to identify soils having different pavement behavior. No pumping was found on the "loess" soils of the "Memphis Series" whereas all pumping was associated with the "Loring Series" where the road was built upon the "B" horizon which is compact and imperfectly drained. The soil test constants for both these soil series do not indicate a wide difference in the physical characteristics.

It will be shown later in this report that the use of significant soil profile characteristics in the basis of a classification of

TABLE 1

Seasonal variation in subgrade moisture-density strength data under a 6-inch pavement. x)

Type of test	1945 July 10 to 15	1945 Oct. 24 to 25	1945 Nov. 23 to 27	1946 Jan. 10 to 11	1946 March 4	Test period average
No. of tests	5	3	2	2	4	-
Avg. moisture, %	20	22	28	29	29	26
Avg. dry density lb./cu. ft.	106	103	95	94	96	99
Avg. saturation percent	89	91	98	96	98	94
Avg. Max. (V-L) kips/sq. ft.	7	5.8	3.5	3.4	4.7	4.9
Percent of July Max. (V-L)	100	83	50	49	67	70
Percent of test Period avg. Max. (V-L)	143	118	71	69	96	100

x) Pavement consisted of 4-inch gravel base with 2-inch bituminous wearing course. All samples were from upper 9 inches of compacted subgrade from an area approximately 55 ft. in length.

#### Subgrade Soil Test Constants

Mechanical Analysis		Plasticity Constants			Moisture-Density Data xa)	
Pass. No. 10	Pass. No. 200	LL	PL	PI	Max. dry wt. lb./cu.ft.	Moisture %
Cum. %	Cum. %					
100	71	51	27	24	105	20

xa) Standard A.A.S.H.O. Method T 99-38.

soils-in-place known as the Pedological Soil Classification. It has been used by certain State highway departments in making pavement performance investigations as well as in the field classification of soils for engineering purposes for over 20 years.

#### ENVIRONMENTAL FACTORS ARE CONSIDERED BY ENGINEERS

It is common practice to apply correction factors to laboratory strength data to compensate for field conditions. Experience has proved that such steps must be taken in the practical application of laboratory strength data to the design of pavements.

Some engineers allow laboratory test samples to soak for a predetermined period of time to simulate the worst soil moisture conditions that might occur under field conditions before making strength tests.

Other engineers 4) feel that those conditions of test are too severe for most environmental conditions found in the field and suggest that design data be obtained from strength tests of undisturbed soil samples or in-place tests made during critical periods of the year.

Wyoming- 5) suggests the use of correction factors to evaluate environmental factors

such as numerical ratings for various ranges of rainfall, depth to water table, degree of frost action, general overall road conditions in the area and estimated traffic. The summation of the numerical rating is used to select a particular design curve showing for the existing conditions the relation between pavement thicknesses and CBR strength data obtained from the laboratory testing of soil samples taken from the road project. Figures 1 and 2 5) indicate how this type of numerical rating is used by Wyoming.

Other engineers suggest the use of pavement performance surveys to establish limitations of various pavement designs under a variety of soil and traffic conditions. The soils are classified on the basis of the pedological soil classification or by significant airphoto soil patterns correlated with geologic landforms and environmental soil characteristics.

Michigan 6) has made effective use of this method of utilizing the pedological soil classification to group soils on an engineering basis. Pavement performance surveys and the correlation of pertinent engineering data and design recommendations with this system of soil classification are the essential items required for their design method.

Table 2 shows how the soil series (fundamental classification unit of the pedological

**TABLE 2**  
**CHART OF SOIL SERIES BY TEXTURE AND ORIGIN**

	BAND AND GRAVEL										LOAM					CLAY				
	Moraine	Esker and Kame	Outwash	TH Plains	Lake Plains	Wind Deposits	Old Shore-Lines	UNDERLAIN BY CLAY			Moraine	Outwash	TH Plains	Shallow Deposition over Outwash	Alluvial and Colluvial Deposits	Lake Plains	Moraine	TH Plains	TH Plains (Water Modified)	Lake Plains
								Outwash	TH Plains	Lake Plains										
WELL DRAINED	Bellefontaine	Bellefontaine	Au Train	Bellefontaine	Au Train	Bridgman	Alpina				Chautauq	Brunson	Beraga	Almook		Alma	Isabella	Isabella		
	Blue Lake	Emmet	Fox	Colma	Esport	Wallace	Esport	Ottawa			Chautauq	Fox	Barber	Beraga		Belleville	Keok	Keok		
	Colma	Kodman	Grayling	Emmet	Plainfield			Ottawa			Hillsdale	Shamhugh	Covestry	Chatham		Tonawanda	Miami	Miami		
	Emmet		Kalkaska	Roadways	Rubicon						Iron River	Waraw	Hillsdale	Crystal Falls				Nash		
	Emmet		Masonville	Vias	Sparta						Monticno		Iron River	Johannesburg				Watts		
	Haverhill		Ontario								Monticno		Schroeder	Langrie						
	Roadways		Plainfield								Monticno		Napamoo							
	Vias		Randville								Monticno		Ontario							
			Rubicon										Oswayo							
			Sparta										Tonawanda							
		Waraw											Somersville							
IMPERFECTLY DRAINED																				
	Esko		Astrim		Saughtick					Armad	Ogawa	Armad								
			Brady							Berrie	Issa	Berrie	Gaston	Ready	Channing	Detour	Gosman	Reinley	Coover	
			Saughtick							Ready		Ready	Gaston	Trot Lake	Mays				Conover	
													Staco						Coldwater	
																			Kawawita	
																			Ontonagon	
																			Conover	
																			Napamoo	
POORLY DRAINED																				
				Oxford	Newton	Newton				Albion	Mussoning	Albion	Adolph	Gifford	Adolph	Dean		Brule	Brule	
				Newton						Gifford									Brookston	
																			Bergland	
																			Brookston	
																			Clyde	
																			Brookston	
																			Brookston	
																			Brookston	
																			Brookston	

**TABLE 3**  
**SOIL ENGINEERING DATA AND RECOMMENDATIONS**

SERIES	BRIEF DESCRIPTION OF TYPICAL PROFILE (See Appendix 2 of Field Manual of Soil Engineering for Complete Description)	TREATMENT																	REMARKS
		GRADE										EXCAVATION							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
Adolph	Partly drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(1) 4 ft below ground surface 1" of gravel is required for drainage.
Albion	Well drained clay loam (sandy)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(2) 4 ft below ground surface 1" of gravel is required for drainage.
Albion	Well drained clay loam (sandy)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(3) 4 ft below ground surface 1" of gravel is required for drainage.
Alpina	Partly drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(4) 4 ft below ground surface 1" of gravel is required for drainage.
Armad	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(5) 4 ft below ground surface 1" of gravel is required for drainage.
Astrim	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(6) 4 ft below ground surface 1" of gravel is required for drainage.
Barber	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(7) 4 ft below ground surface 1" of gravel is required for drainage.
Beraga	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(8) 4 ft below ground surface 1" of gravel is required for drainage.
Berrie	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(9) 4 ft below ground surface 1" of gravel is required for drainage.
Bridgman	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(10) 4 ft below ground surface 1" of gravel is required for drainage.
Brookston	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(11) 4 ft below ground surface 1" of gravel is required for drainage.
Brunson	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(12) 4 ft below ground surface 1" of gravel is required for drainage.
Chatham	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(13) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(14) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(15) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(16) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(17) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(18) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(19) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(20) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(21) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(22) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(23) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(24) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(25) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(26) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(27) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(28) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(29) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(30) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(31) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(32) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(33) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(34) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(35) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(36) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(37) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(38) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(39) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(40) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(41) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(42) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(43) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(44) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(45) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(46) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(47) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(48) 4 ft below ground surface 1" of gravel is required for drainage.
Chautauq	Well drained clay loam	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	(49) 4 ft below ground surface 1" of gravel is required for drainage.

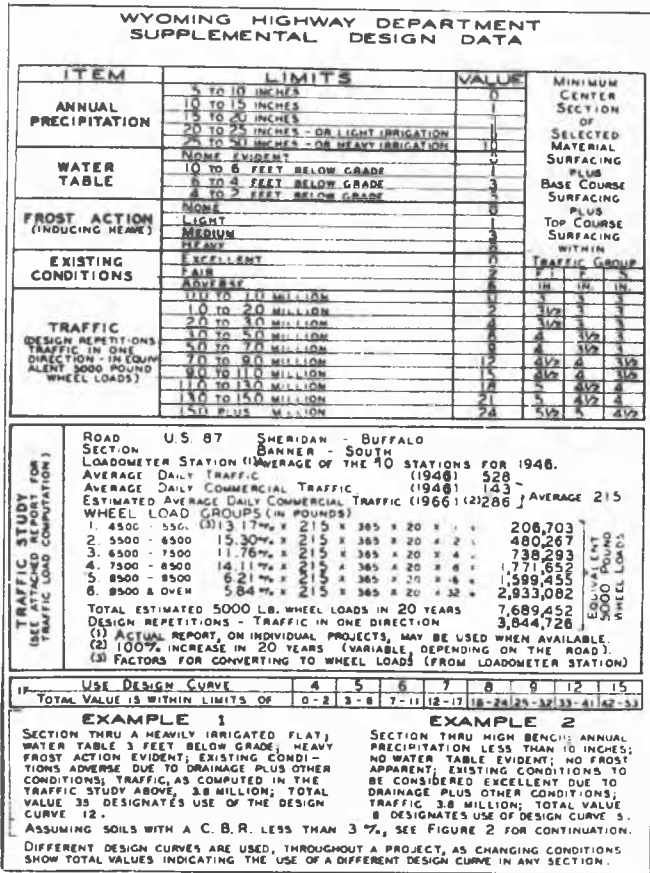


FIG. 1

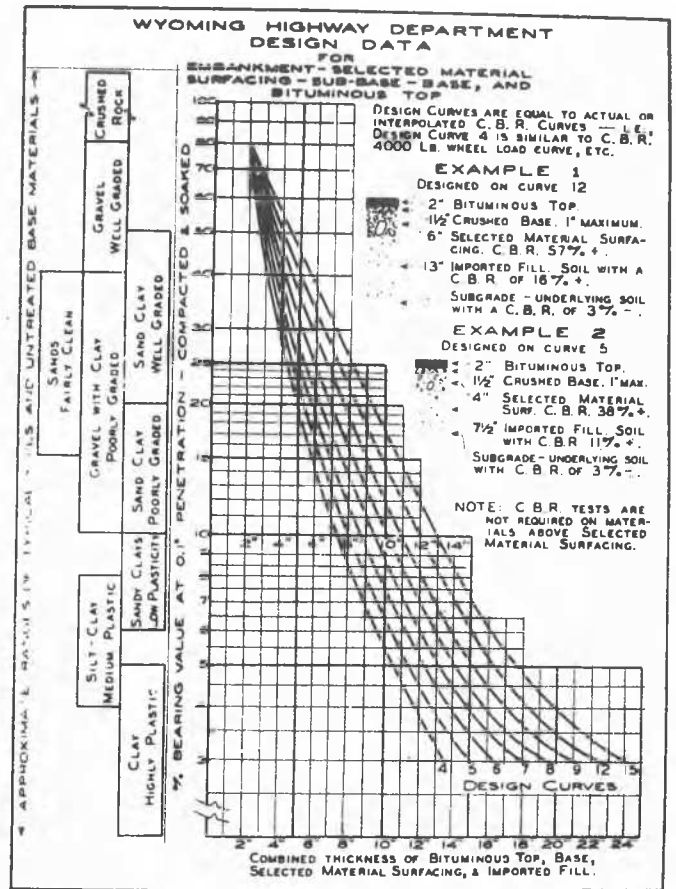


FIG. 2

equipment and personnel, and the time required for testing soils in the laboratory restricts the number of samples that can be tested for any particular project. Consequently, emphasis must be given to the engineering appraisal of soils in the field, especially the pavement behavior of roads that have been built over similar soil conditions.

Where States have adequate coverage of county agricultural soil maps or have men trained in the identification of soils in the field by the pedological soil profile characteristics, the Michigan method can be effectively used to obtain a maximum of pertinent engineering information with a minimum of testing. With this method of approach, the major portion of the work will be accomplished in the field at the time the detailed soil surveys are made for the road projects.

If the State has good airphoto coverage, a good geological map and limited coverage of agricultural soil maps, the airphoto soil pattern method as suggested by Indiana may be more satisfactory for identification of soils requiring similar engineering treatment. The major portion of the work can be done in the laboratory by a highly trained technician but it should be supplemented with a limited amount of ground reconnaissance and include representative sampling and testing of soils for each significantly different airphoto soil pattern.

In areas where soils are poorly developed and either airphoto or county soil maps coverage is limited, the use of Wyoming method may be the logical approach. The major portion of the work is likely to be in the field making appraisal of the environmental factors. The effectiveness of this method appears to rest in the ability of the engineer to judge these correction factors properly.

It is believed that a soil engineer can estimate the effect of environment in a land area more accurately through the identification from soil profile characteristics (pedological system of soil classification) than can an engineer using generalized climatic data and average data on the position of water table and degree of frost heaving for the same land area.

**SUMMARY**

- 1) There is a need for additional studies of the soil moisture-density-strength relations on a seasonal basis for a wide range in soil textures and climatic conditions. These studies should be made on subgrades of pavements of several types and thicknesses so that the effect of insulation can be correlated with seasonal changes in the strength of subgrade soils.
- 2) The use of average annual rainfall data as a design factor might be misleading under certain conditions. Different external and internal drainage conditions develop on similar parent materials under the same annual rainfall if the slope of the land surface (relief) differs significantly in the area.
- 3) The use of the system of land classification by soil series will reflect these drainage conditions more accurately than a generalized weather map showing average annual rainfall data.
- 4) It has been found that environmental factors affecting the strength of subgrades must be considered in the design of pavements as well as laboratory strength data. It is common practice to apply correction factors to a generalized design formula to compensate for field conditions.

5) The use of a numerical rating system based upon the engineer's judgment of terrain factors, traffic, and climatic conditions; the use of pavement performance surveys and soil information correlated with soils classified on the basis of soil profile characteristics (pedological classification); or the use of pavement performance surveys and soil information correlated with significant airphoto soil patterns appears to be the most practical methods of evaluating the effect of environmental factors likely to affect the strength of subgrade soils.

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### THE PREPARATION OF SUBGRADES OF COMPACTED SOILS FOR PAVING OR STRUCTURES

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VIII f 7

#### SYNOPSIS

The almost universal practice of preparing subgrades for paving or structures by compacting with a sheepsfoot roller (of widely varying weights and designs) until the top of the loose surface of the fill is at approximate subgrade elevation, and then completing the compaction by the use of one of many types of flat rollers to prepare the final subgrade includes two fundamental errors. First, the full compactive effort of the sheepsfoot roller is not secured closer than 10 inches to the fill surface and the flat rollers used cannot compact this top 10 inches of the fill to as high a density (dry weight) as can the sheepsfoot roller (about 50 lb per sq in indicated saturated penetration resistance, to be compared to a value as high as 700 lb per sq in with properly designed and used sheepsfoot rollers), and thus a layer of potential mud or near mud (about 50 lb per sq in penetration resistance in case of subgrade saturation) is left to serve as the foundation for the paving or structure. Second, the weight of the roller causes some consolidation, not compaction, of the soil at a distance from 1 to 4 ft from the loose surface of the fill; and this process of consolidation by sheepsfoot roller is not completed closer than 4 ft, or may be a little more, from the fill surface. Subsequent traffic or structure loads continue the consolidation. Present day practices of placing rock "base courses" to considerable depths under pavings to overcome the above compaction deficiencies, does not differ importantly from the road building methods of Caesar; it appears to be time for a modernization of road building methods that takes into account some of the recent progress in the field of soil mechanics. It is the purpose of this discussion to point out possible ways and means of eliminating the two foregoing errors in the preparation of subgrades.

#### INTRODUCTION

For the purpose of this discussion it will be assumed, by definition, that sheepsfoot rolling, in similar fashion to dry rodding of sand, compacts, and that pneumatic tires, flat rollers, and foundation loadings consolidate. These different actions in compacted fills are not well understood; referring to Fig. 1, the resulting soil dry weight from compaction over a wide range of sheepsfoot roller exerted compactive efforts is shown, and then the additional consolidation per foot of depth of fill that will take place under a static loading of 50 lb per sq in is also shown by the small figures to the left of the zero air voids curve. It is believed that neither compaction nor con-

solidation alone can achieve suitable subgrades, particularly for pavements and especially for structures that may have a vibratory loading. A compacted soil will consolidate and likewise a consolidated, but not compacted, soil will compact if its structure is disturbed after it is consolidated; an illustration of this can be found in that equipment traveling on a soil that has been consolidated while fairly dry under pneumatic tired rolling will continue to go down under the action of pneumatic tires when the soil becomes saturated unless it is compacted to a greater density than is generally achieved (above 350 lb per sq in saturated penetration resistance).