Properties of Field Compacted Soils

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Soil compaction tests were conducted in the field by constructing test sections of soil in single lifts on a prepared foundation using a variety of commercial rollers. The test results were obtained using the following specific independent variables: (a) four subgrade soils, A-6(13), A-6(9), A-4(1) and A-4(8); (b) four moisture contents for each soil ranging from dry to wet of optimum; (c) two lift thicknesses, 6 and 12 in.; (d) four rollers, sheepsfoot, pneumatic tire, vibratory smooth-wheel, and segmented pad, at two levels of effort for each roller; and (e) roller coverages up to 16. Measurements were made of the strength, stiffness and density of the soil using a variety of techniques. A full factorial experiment consisting of 256 test sections to represent all combinations of these selected variables was designed to detect, using analysis of variance techniques, the effects of the variables on the measured soil properties, taking into account the large variability existing in the field. The results describe the measured CBR, penetration resistance, bearing stiffness, seismic velocity and density, and show how they were affected by the test variables. The CBR and density are also compared with the values obtained using standard laboratory tests.

•A research program was undertaken to investigate the properties of field compacted soils and the factors involved in construction which influence these properties. Tests were carried out in the field in an attempt to simulate many of the environmental and operational conditions encountered in construction. Details of the test plan and procedures are described in a companion paper in this RECORD (1). A general familiarity with that paper will be assumed. The methods of measurement are evaluated in another companion paper (2).

The results discussed in this paper were obtained from the statistical analysis of the principal series of tests on the subgrade soils. These provided 256 test sections combining the following variables:

1. Four soils—moderately plastic clay, silty clay, silty sand and gravel, and silt.
2. Lift thicknesses of 6 and 12 in.
3. Four moisture contents bracketing the laboratory standard and modified Proctor optimums.
4. Four compactors—intermediate pneumatic, intermediate vibratory, segmented pad and self-propelled sheepsfoot.
5. Two levels of compactive effort for each roller.
6. Soil preparation by a pulverizing mixer.

Standard compaction tests were conducted on each of the four soils in the laboratory, and the modified Proctor tests were repeated in the field using samples taken from the prepared lifts. In both cases unsoaked CBR tests were performed on the compacted specimens.

Paper sponsored by Committee on Compaction and presented at the 46th Annual Meeting.

Single lifts were prepared containing four test sections, one for each nominal moisture level. Initial moisture content was measured in each test section. After 2, 4, 8 and 16 coverages with a roller, the following measurements were made in each test section:

1. Average penetration resistance through lift.
2. Load on 6-in. diameter bearing plate causing 0. 1 in. sinkage.
3. Seismic velocity.
4. Wet density and moisture density (moisture content in lb/cu ft of water) with a backscatter nuclear instrument.
5. Wet density and moisture density with a nuclear Road Logger.

At the completion of 16 coverages the lift was stripped to approximately one-half of its thickness and the measurements repeated (the penetrometer measurements were taken before stripping). In addition, final moisture content and CBR were measured and sand cone tests performed on two of the four test sections.

This paper discusses the factors which significantly affected the measured properties, the magnitude of the effect, the nature of the growth curves, and the correlation between the different types of measurements.

EFFECT OF INDEPENDENT VARIABLES ON PROPERTIES

The independent variables and number of levels of each variable considered in the field tests were: moisture—4, lift thickness—2, soil—4, compactive effort—2, and compaction equipment—4. A statistical analysis using analysis of variance techniques was conducted to determine which of these independent variables influenced the measured properties and the magnitude of these effects. The statistical model for the analysis was constructed so that the joint effects of any two of these variables could be determined, as well as the individual effects of each alone. In addition, the variability associated with each measurement was estimated. It must be kept in mind that the measurement techniques also may have a considerable influence on the results; therefore, to the extent that these latter effects are correlated with the independent variables in a manner which cannot be predicted, then the observations will be biased. A discussion of the variability and methods of measurement is contained in a companion paper (2).

Table 1 lists the soil measurements and ranks the effects of the independent variables in order of significance. In addition to the five independent variables, the ten possible combinations of these variables are included. (The independent variables are designated as follows: M = moisture level, T = lift thickness, S = soil type, C = compactive effort, and E = compaction equipment. Combinations of any two letters indicate joint effects.) The significance is expressed in terms of a probability of error in an assumption that the given variable really affects the measurement rather than being a chance occurrence. The categories range from less than 0. 1 percent to 10 percent. Traditionally, a 5 percent limit is often selected as an upper bound, but for this analysis the limit was extended to 10 percent. Any unmarked variable exceeds that limit.

The effect on the measured values in Table 1 was based on analyses of the data from individual coverages and also the average of coverages 2, 4, 8 and 16 when such data were available. When several analyses were made for a particular measurement, the results were combined and the lowest error probability (highest significance) for each effect was shown in the table.

Moisture Content and Field Proctor Tests

The initial moisture content and sand cone moisture content, and the wet density, moisture content and CBR from the field Proctor test, were examined as a group to determine the possible existence of any unwanted bias in the test results. Only the moisture content (M) and soil (S) independent variables should be significantly correlated with these measurements, according to the test plan. Any other significant effects

TABLE 1

RELATIVE SIGNIFICANCE OF INDEPENDENT VARIABLES ON SOIL MEASUREMENTS

Measurement	Individual Effects					Joint Effects									
	M	T	S	C	E	MT	MS	MC	ME	TS	TC	TE	SC	SE	CE
Initial w(%)	1		1	6			4								
Sand cone w(%)	1		1												
Proctor w(%)	1		1				2								
Proctor γ_w	1		1				1								
Proctor CBR	1		1	4	4		1								5
Portable nuclear γ_w	1		1		1				1					6	
Portable nuclear w_d	1		1	6	1		5		1						5
Portable nuclear γ	1		1		1		5		1			6		6	6
Road logger γ_w	1	2	1	6	6				5			5			5
Road logger w_d	1		1						4						3
Plate load	1	3			1		1	5	2						5
Pen. resistance	1		1		1	6	1		4			1			
Seismic velocity	1	4	6		6		1	6	1						
Field CBR	1	5					6					4			

Note: Error Probability (%): 1 = 0.1, 2 = 0.5, 3 = 1.0, 4 = 2.5, 5 = 5.0, 6 = 10.0.
γ_w = wet density, γ_d = dry density, w = moisture content (%), w_d = moisture density.

would be present by chance and might distort the data interpretation. Table 1 shows that for each of the five measurements the effects of M and S were highly significant (at the 0.1 percent level), and the only other consistent effect present was the joint interaction of moisture and soil (MS). For the three moisture measurements no other effects were significant, except for compactive effort (C) in one case where it was just significant at the 10 percent level.

Of the five measurements only the CBR showed important deviations from the expected behavior. Compactive effort (C), equipment (E) and their joint interaction (CE) were significant at the 2.5 and 5 percent levels. The explanation for this occurrence, in view of the results with the other four measurements and an examination of the data, appears to be some chance correlation in the CBR test and not a bias in the test plan itself.

The relationships for the Proctor wet density and CBR will be discussed later. The relationship between the measured moisture contents for the three methods and the prescribed levels of M and S are shown in Figure 1. The results show a continuous increase in moisture content with moisture level. The increase with soil type for each moisture level is in the same order as the optimum moisture contents from the Proctor test. For all four soils the T-99 optimum is bracketed and, except for the clay, the T-180 optimum is also bracketed. The clay was wetter compared to its optimum than the other soils and the silt was dryer.

Nuclear Moisture and Density

The wet density (γ_w) and dry density (γ_d) measurements from the portable nuclear gage and the Road Logger on the compacted lifts were all affected by the variables M and S at the most significant (0.1 percent) level. The compaction equipment had a highly significant effect on the portable nuclear density measurements, although it was only significant at the 10 percent level for the Road Logger. Joint effects of ME, TE, SE, and CE for wet density and MS and SE for dry density were also present for the nuclear devices. The results are shown in Figure 2.

The wet density increases continuously with moisture level, hence the compaction appears to be dry of optimum on the whole for the compactive efforts used. The wet density also increases with respect to soil type in the same order as the Proctor maximums, except for the silt, which gave the lowest value instead of lying between the clay and the silty clay. The main reason for this is that the silt was compacted drier of optimum than the other soils (Fig. 1), and the clay was compacted closest to optimum

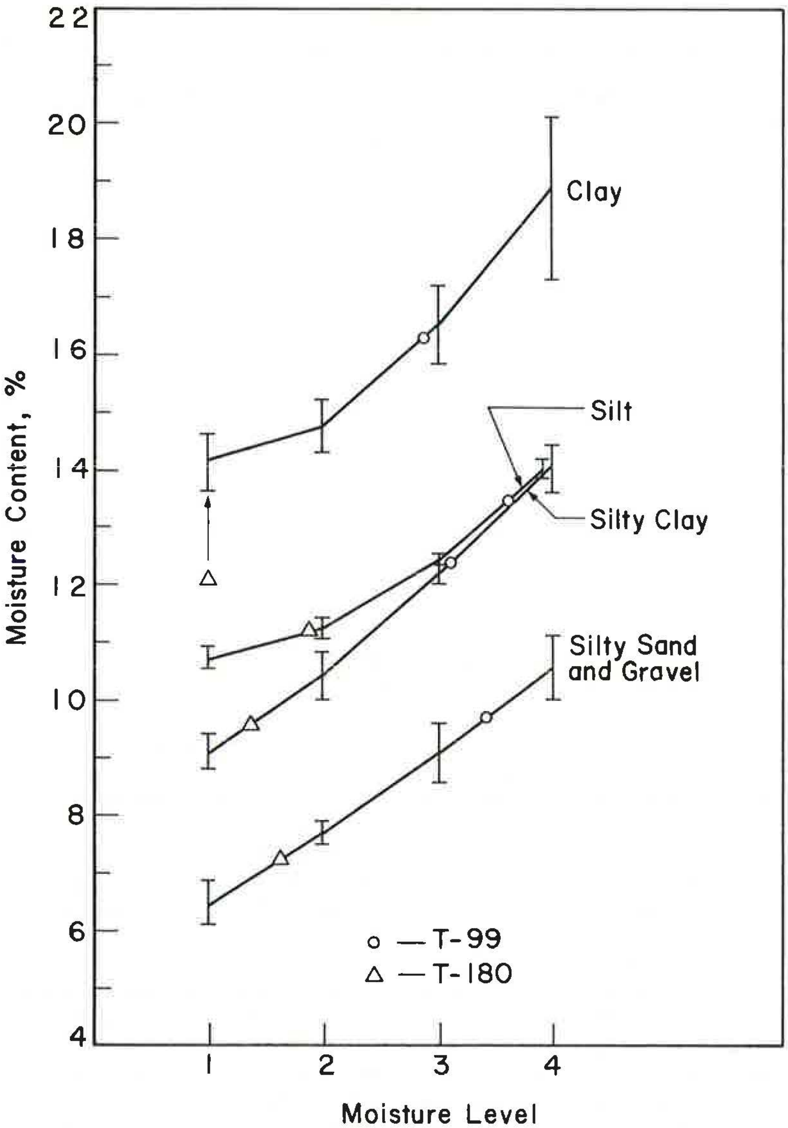


Figure 1. Moisture variation with moisture level and soil type.

for the average compactive effort. But this situation could also result if silt did not compact as effectively as the other soils. The dashed line in Figure 2 indicates the probable relationship if the moisture contents for all of the soils were the same relative to their respective optimums.

The sheepsfoot (S), pneumatic (P), and vibratory (V) rollers statistically gave about the same wet densities, and the segmented pad (T) roller gave significantly greater values on the average (Fig. 2). The values shown are averages for all soils, compactive efforts, moisture levels and lift thicknesses used in the tests. The relative relationships between the results for the four compactors will change with the specific conditions. The segmented pad roller, which gave the highest overall density, was the heaviest roller of the four, even at its lowest compactive effort. In addition, the results with the sheepsfoot roller are undoubtedly influenced adversely by using single-lift test sections.

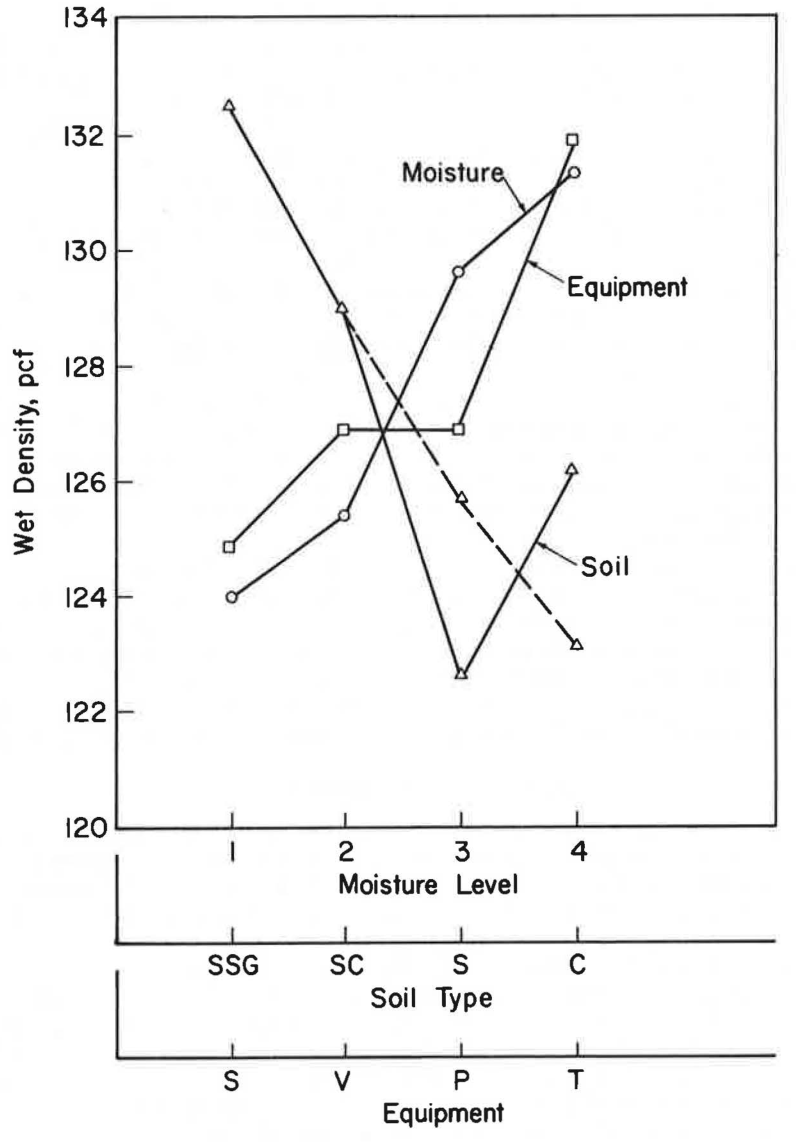


Figure 2. Final wet density variation with moisture, soil and equipment.

The joint effect ME was caused by a greater change in wet density over the existing moisture range for the pneumatic and vibratory rollers than for the sheepsfoot and segmented pad rollers. The MS effect was primarily a result of the difference in the relationship of the moisture range to the optimum moistures for each soil type (Fig. 1). The presence of an SE effect indicates that the relative performance of the rollers changes with soil types. The highest wet densities in each case were obtained with the segmented pad roller. For the silty clay, silt and clay the other three rollers gave lower values not significantly different from each other. However, for the silty sand and gravel the vibratory roller equaled the results with the segmented pad roller; the pneumatic roller did almost as well.

The Road Logger also showed a highly significant effect of T and C. The wet density decreased an average of about 5 pcf with an increase in T from 6 to 12 in., and increased an average of 3 pcf with an increase in compactive effort. The portable nuclear instrument showed the same trends, but the magnitude of the change was not large enough to be significant at the 10 percent level or better. The joint effect TE occurred because the overall reduction in wet density with T increase was caused primarily by the pneumatic and segmented pad rollers, whose effect was 6 and 8 pcf, respectively. There was a tendency for a decrease in wet density with C for the sheepsfoot roller, little effect of C for the vibratory roller and significant increases of 6 and 7 pcf for the segmented pad and pneumatic rollers, thus causing the CE effect.

The moisture density (w_d) with both nuclear instruments was affected by M and S at the highest level of significance. The trends were similar to those for the moisture content given in Figure 1. For the portable nuclear instrument, E was also a highly significant factor, but this was entirely caused by high readings obtained during the compaction of lifts with the sheepsfoot roller. The stripped measurements on these lifts were back in line with those for the other rollers—eliminating the E effect. The interaction effects for ME were present in each case, because of the interrelationship between the amount of compaction and the distribution of moisture content for each roller. The trends are the same for each roller, however. The MS effect reflects a difference in the distribution of moisture over the four levels with change in soil type. This is indicated to some extent in Figure 1. In several cases, the nuclear instruments indicated a change in ranking with respect to moisture density for the silt and silty clay as the moisture level changed.

The effect of C on moisture density was cause by a slightly higher (0. 5 to 0. 9 pcf) moisture density at the higher compactive effort than at the lower one. The significance of the joint effect CE resulted because the effect of C changed with the roller type. The pattern was the same as that for wet density, i. e., increase entirely due to the pneumatic and segmented pad rollers, no change for the vibratory roller, and a decrease for the sheepsfoot roller. Moisture density increases with both increased compaction and increased moisture content. Both probably contributed to the observed CE effect.

Penetrometer, Plate, CBR and Seismic Measurements

Moisture was the most significant factor influencing the strength and stiffness properties, since it was significant at the highest level for all such measurements, i. e., penetrometer, plate, CBR and seismic (Table 1). The effects of the remaining factors are not nearly as consistent; however, the factor ME was significant in all cases and the factors T, E, and MS were significant in three out of the four cases.

The general relationship between M and the final measurement of seismic velocity, penetration resistance, bearing plate load and field CBR is shown in Figure 3. All but the seismic velocity show a consistent decrease with increase in moisture level as expected. The seismic velocity increased up to the third moisture level and then decreased. The trend is more like that of dry density than strength or stiffness. The same trend was evident for the average of the growth measurements.

There was a consistent decrease in the measured properties for an increase in lift thickness from 6 to 12 in., except for the penetrometer. This trend for CBR held for all S, C and M. There was a TE effect because the decrease was all caused by the pneumatic and segmented pad rollers. There was no change for the vibratory roller and a small increase for the sheepsfoot roller. The magnitude of the decrease diminished with increasing M. This trend was not detected from the average of the growth measurements for seismic velocity, but it was exhibited by the final measurements for all M, S, C and E. Again the decrease diminished with M. The average of the bearing plate growth measurements showed a consistent decrease with thickness increase for all M, S, C and E, although the changes were not large enough to be statistically significant. The same general trend was exhibited by the final plate readings, except for a slight increase for the vibratory and sheepsfoot rollers.

The penetrometer did not show a significant T effect for either the growth or final measurements. However, there was an effect of T in relation to M and E. The resistance increased with T for all but the third moisture level. According to the TE effect, there was a large increase in resistance for the sheepsfoot roller and a consistent decrease for the segmented pad rollers. For the pneumatic and vibratory rollers, the

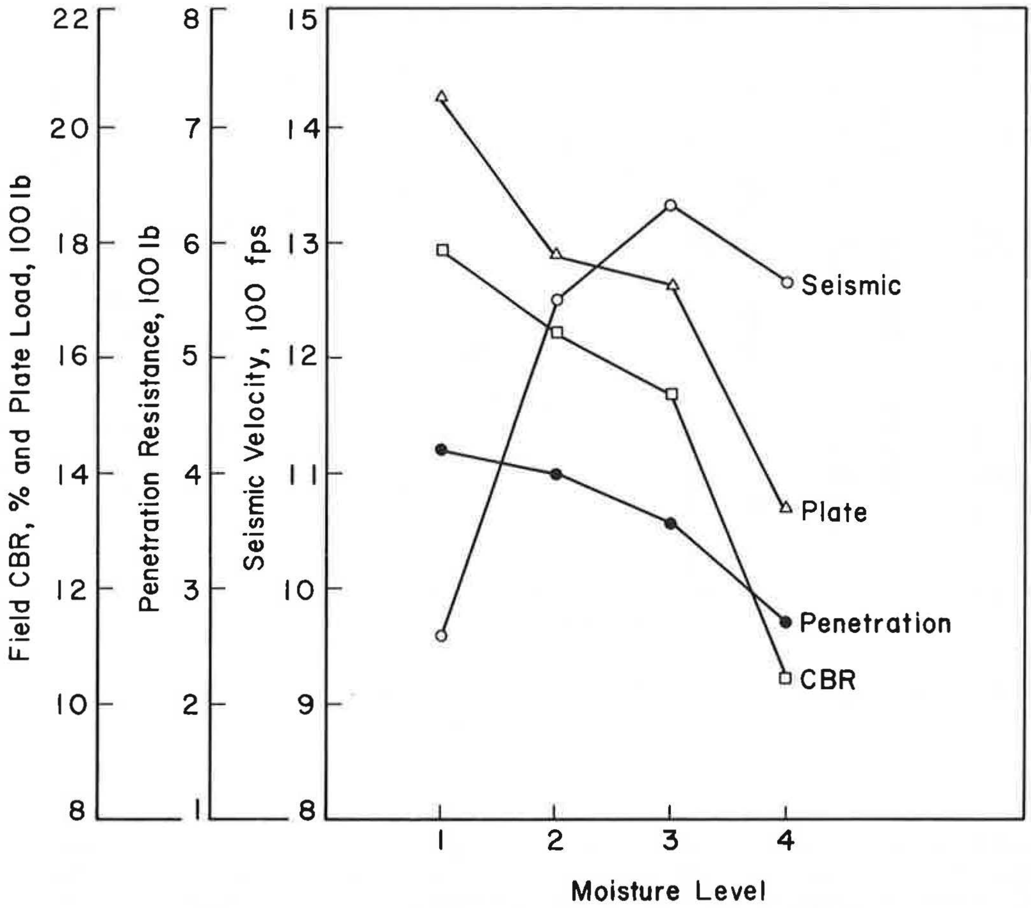


Figure 3. Penetration resistance, CBR, plate load and seismic velocity variation with moisture level.

change was either negligible or inconsistent. Considering the other three measurements, these observations suggest that side friction on the penetrometer shaft may have influenced the readings.

The factor C, itself, did not have a significant effect on any of the four measurements, although the general trend was an increase with increased effort; however, the joint effects with M, S and E were present in some cases. The significant effects of S and E are shown in Figure 4. The penetration resistance decreases with soil type in the order: silty sand and gravel, silty clay, silt, and clay, which is the same order as decreasing maximum dry density from the Proctor test. The seismic velocity follows the same trend for the first three soils, but the clay has the next to highest velocity. The effect of E on plate load, seismic velocity and penetration resistance is similar to that for wet density; i. e., the sheepsfoot, pneumatic and vibratory rollers gave results not significantly different from each other, while the values for the segmented pad roller were significantly higher.

The joint effect CE was significant for the bearing plate only. This was caused by a decrease for the segmented pad roller with increased compactive effort. This trend was also indicated by the penetrometer. The effect for the sheeps foot roller was mixed, while for the vibratory and pneumatic rollers there was a tendency for the properties to increase with compactive effort.

The final plate load increased with compactive effort for the two lowest moisture levels and decreased for the two highest levels, giving an MC effect. However, seismic velocity indicated an increase with compactive effort at all four moisture contents. The

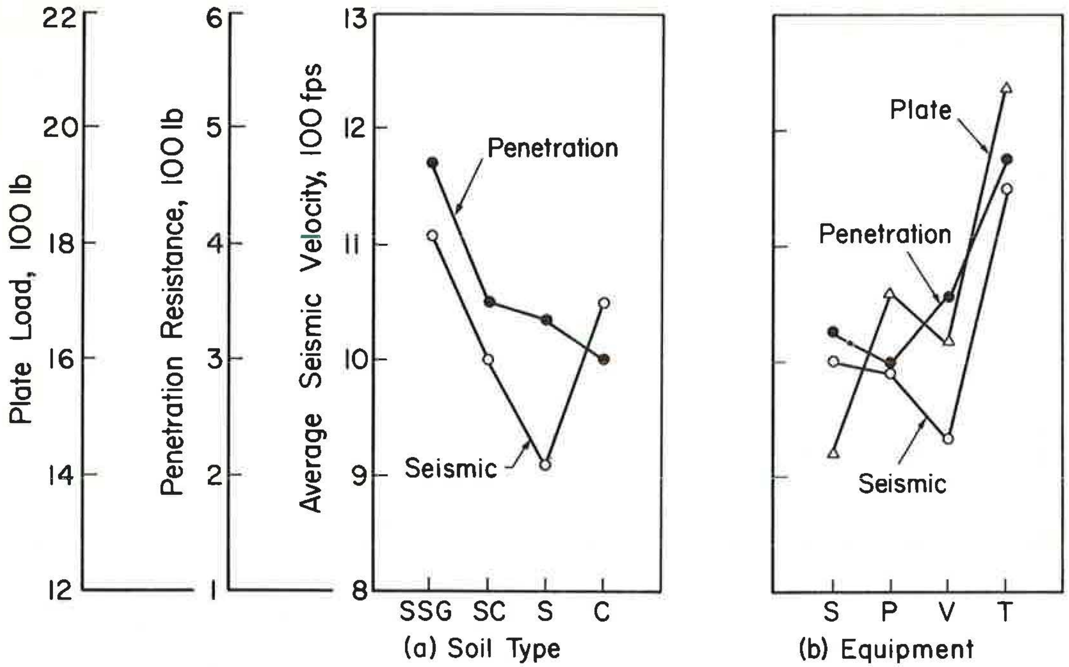


Figure 4. Penetration resistance, plate load and seismic velocity variation with soil type and compaction equipment.

plate load, penetration resistance and CBR decreased with M in the general manner shown in Figure 3 for the silty sand and gravel, silty clay and clay. However, these values did not change significantly for the silt, thus giving rise to an MS effect. The seismic velocity followed the general pattern of Figure 3 for all soils at the end of compaction, but there was little change for the average of the growth measurements for silt, thus creating the MS effect. For the plate load and penetration resistance, the trend in Figure 3 was followed for each roller, except that there was a maximum in the middle range of moisture levels for the vibratory roller giving an ME effect. The ME effect for seismic velocity occurred because of a change in the position of the maximum within the range of moisture.

TABLE 2

RANGE AND AVERAGE OF PROPERTIES FOR ALL EFFECTS

Measurement	Dimension	Range	Average	Range / Average (%)
Moisture content	%	13.5	12.1	112
Field CBR	%	26.6	15.0	177
Wet density	pcf	29.8	127.6	23
Moisture density	pcf	10.9	12.6	87
Dry density	pcf	21.5	115.0	19
Penetration resistance	lb	529	364	145
Seismic velocity	fps	890	1192	75
Plate load	lb	1814	1719	105

Range of Values

The overall range and average of each of the measurements for the range of independent variables used in the tests are shown in Table 2. The average values were obtained by pooling all of the final measurements in each case for all of the test sections. The range was determined by subtracting the largest and smallest estimated mean values from the group representing all of the combinations of independent variables.

The largest change with respect to the average value occurs for the field CBR, whose range is 177 percent of its average. Next in decreasing order are the penetration resistance, moisture content and plate load which have ranges exceeding 100 percent of their average values. Moisture density and seismic velocity range about 80 percent of their averages. As expected, the property which changes the least with respect to its magnitude is density, the wet and dry densities having a range of about 20 percent of their average values. It might be expected that the best properties to measure are those whose percentage change is the largest; however, such a conclusion depends on the associated measurement variability. This latter question is examined in a companion paper (2).

CHARACTERISTICS OF GROWTH CURVES

The remaining independent variable, which has not been involved in the previous discussion, is the number of roller coverages. The mathematical model used in the analysis was so constructed that the shape of the growth curves for each measurement could be evaluated independently of the magnitude of the measurements. The factors influencing the shape of these curves are given in Table 3 in the same manner as was done for the measurements themselves in Table 1.

Portable Nuclear Measurements

The individual factors affecting the shape of the wet density growth curves obtained with the portable nuclear instrument were S, C and E. The curve shapes for S and E are shown in Figure 5. In order to establish the actual quantitative relationship between the curves in a set, the indicated mean value of each curve should be added. This will shift the curves vertically without a change in shape. By removing the mean values the comparison of shapes may easily be made; e.g., if the shapes are identical then the curves will be coincident regardless of the magnitude of the measurements.

Figure 5a shows that the vibratory and pneumatic rollers had achieved their maximum amount of compaction by the end of 16 coverages for all four soils on the average, but density was still increasing at a significant rate for the segmented pad and sheepsfoot rollers. However, in terms of absolute density, the sheepsfoot roller was still at the lowest level at the end of 16 coverages, because its mean value of wet density was much lower than those for the other three rollers. Increase in density was still occurring

TABLE 3

RELATIVE SIGNIFICANCE OF INDEPENDENT VARIABLES ON GROWTH CURVE SHAPE

Measurement	Individual Effects					Joint Effects									
	M	T	S	C	E	MT	MS	MC	ME	TS	TC	TE	SC	SE	CE
Portable nuclear γ_w			2	6	1	6	4		5						
Portable nuclear w_d					6		6								
Portable nuclear γ_d				6	1		6		5					3	
Plate load	1				1								6	5	6
Pen. resistance	1		4				5	5							6
Seismic velocity	2					5	2		2						

Note: Error probability (%): 1 = 0.1, 2.= 0.5, 3 = 1.0, 4 = 2.5, 5 = 5.0, 5 = 5.0, 6 = 10.0.

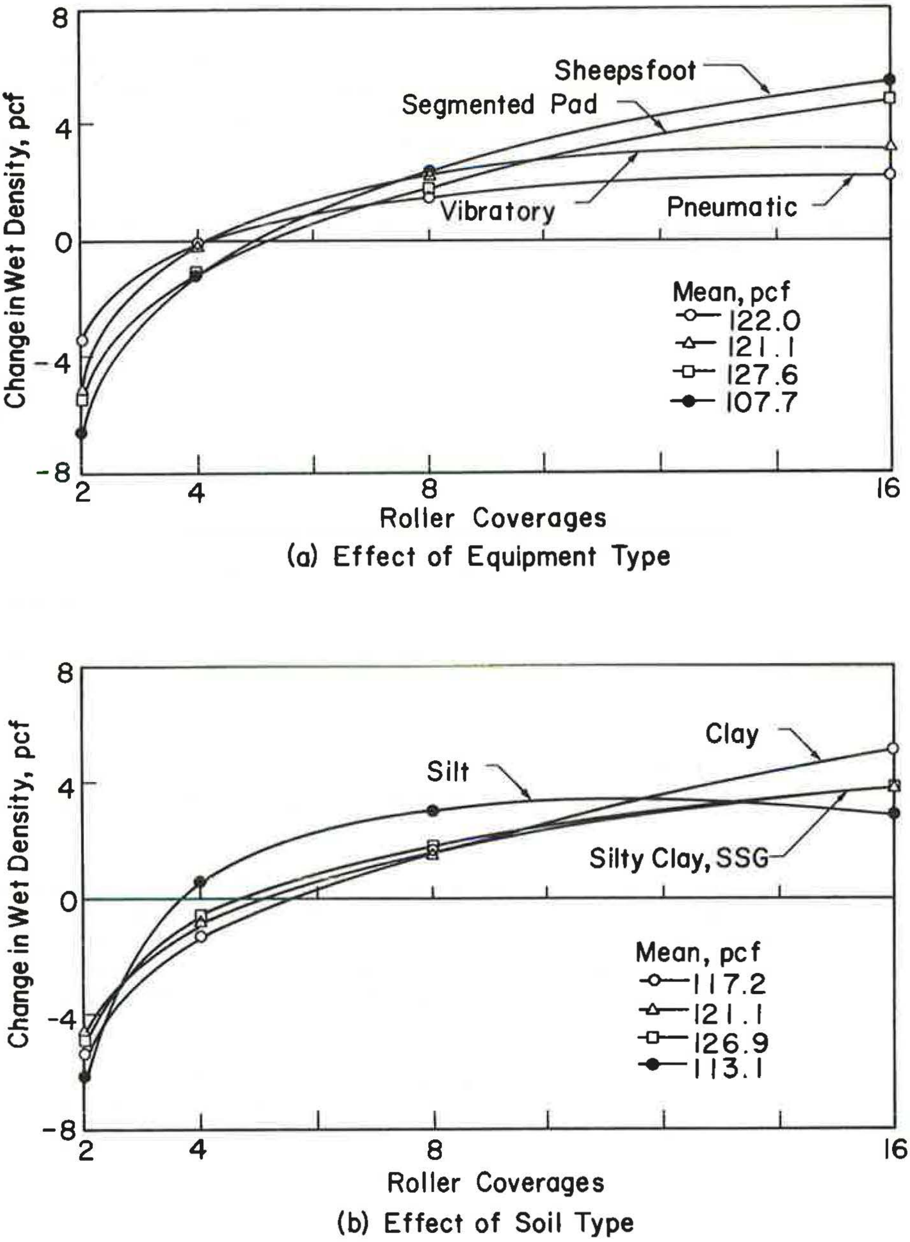
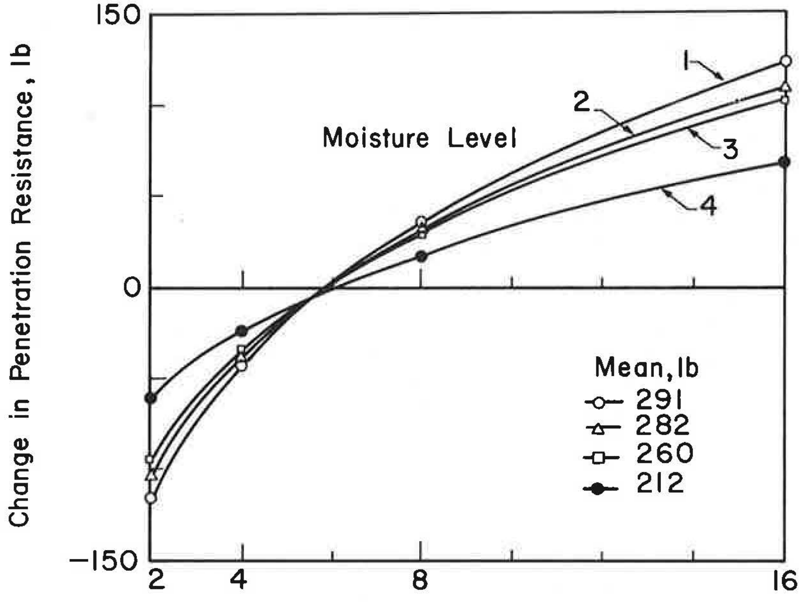


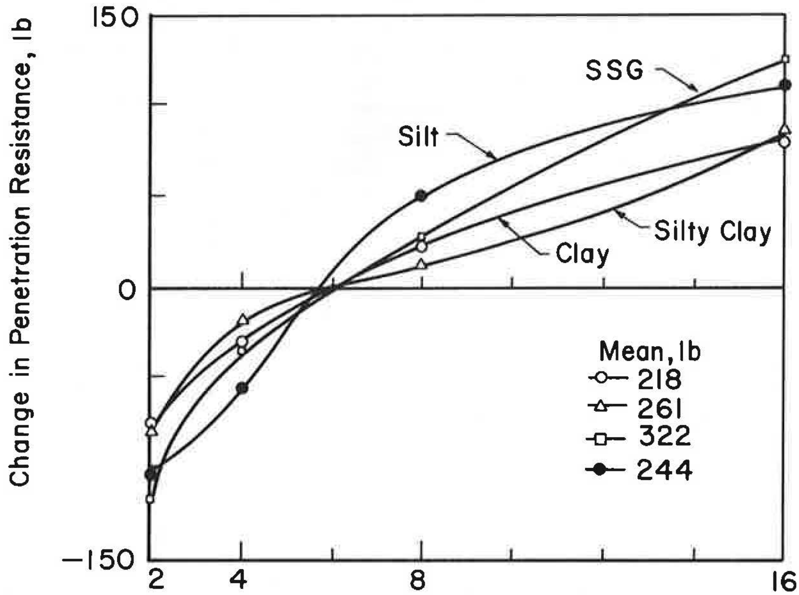
Figure 5. Average portable nuclear wet density growth curves for compaction equipment and soil type.

for the clay, silty clay and silty sand and gravel (Fig. 5b) at the end of 16 coverages, with the greatest change being in the clay. The silt compacted at a greater rate initially, but reached a maximum wet density at about 10 coverages and then began to show a decrease. The compaction occurred at a slightly greater rate for the higher compactive effort than for the lower, but the difference was small.

The MT effect indicates that with the 6-in. layer the rate of compaction increased with increase in moisture level; for the 12-in. layer, the reverse was true. Only the curve for the highest moisture in the 6-in. lift had reached a maximum by 16 coverages. The fact that M alone did not affect the shape suggests that the resulting



(a) Effect of Moisture



(b) Effect of Soil

Figure 6. Average penetration resistance growth curves for soil type and moisture level.

moisture-density curves had the same shape after every coverage on the average. For each individual soil, however, moisture did influence the shape. This MS effect may reflect the relationship of the actual moisture content to the optimum for the soil and compactive efforts involved. The ME effect indicates a change in the effect of moisture on the shape with change in compactor.

The growth curves for clay, silty clay, and silty sand and gravel were generally the same within each equipment group, although the clay density was always increasing at the greatest rate for each roller after 8 coverages. The silt curves were the most distinct and were the principal reason for the SE effect. The silt density was still increasing some after 16 coverages for the segmented pad roller. For the pneumatic and sheepsfoot rollers the curves leveled out after 8 coverages; however, for the vibratory roller there was a distinct decrease.

Theoretically, moisture density should increase with roller coverages in the same manner as wet density; however, the change is small enough with respect to the accuracy of the measurement that it can be considered constant in most cases. The change from 2 to 16 coverages for the pneumatic and segmented pad rollers was an increase of less than 0. 2 pcf and for the vibratory roller an increase of less than 0. 6 pcf. For the sheepsfoot roller, the moisture density decreased about 1 pcf. The MS effect was inconsistent, showing a decrease with coverage more often than an increase, the maximum change being 1 pcf in any case.

Penetrometer Measurements

The rate of increase of penetration resistance with coverage decreased continuously with moisture level increase (Fig. 6a). As a result, the total change in resistance between 2 and 16 coverages decreased with moisture increase. The shapes had much less curvature than those for density. The penetration resistance curves for the clay, silty clay, and silty sand and gravel were similar to those for wet density, except for less rapid initial rate of change (Fig. 6b). The shapes for silt were quite different, however. For this soil the penetration resistance changed in an approximately linear fashion up to 8 coverages and then continued to increase at a slower rate thereafter. At the higher compactive effort there was less difference between the shapes for each moisture level than at the lower effort.

The shapes of the penetration resistance curves for the four compactors were similar, although the segmented pad roller showed the greatest rate of increase at 16 coverages and the greatest change from 2 to 16 coverages. The lowest rate and smallest change occurred for the pneumatic roller. The CE effect was produced by the sheepsfoot roller, whose growth curve changed in shape with change in compactive effort. The overall trend was the same as that for the other rollers, but it had a double curvature which reversed direction with change in C.

Bearing Plate Measurements

The most significant factors influencing the bearing plate growth curve shape were E and M. As with the penetrometer, the rate of increase of plate load decreased with increase in moisture (Fig. 7a). The biggest difference occurred between the third and fourth moisture levels. The pneumatic and segmented pad rollers gave the greatest increase and rate of increase of the four compactors over the range of 2 to 16 coverages. Next in order was the vibratory roller and then the sheepsfoot roller (Fig. 7b). In most cases the plate load was still increasing at a significant rate after 16 coverages.

The difference in the growth curve shapes for the four soils decreased with increased compactive effort. The same was true for the compaction equipment. The difference in growth curves for the sheepsfoot roller in the four soils was small. The vibratory roller showed the greatest change from 2 to 16 coverages for the clay and essentially identical results for the other three soils. The pneumatic roller showed the greatest change for the silt and the same results for the other three soils. All four soil curves were different for the segmented pad roller.

Seismic Velocity

The only individual factor affecting the shape of the seismic velocity growth curves was moisture. The greatest change in velocity occurred for the two intermediate mois-

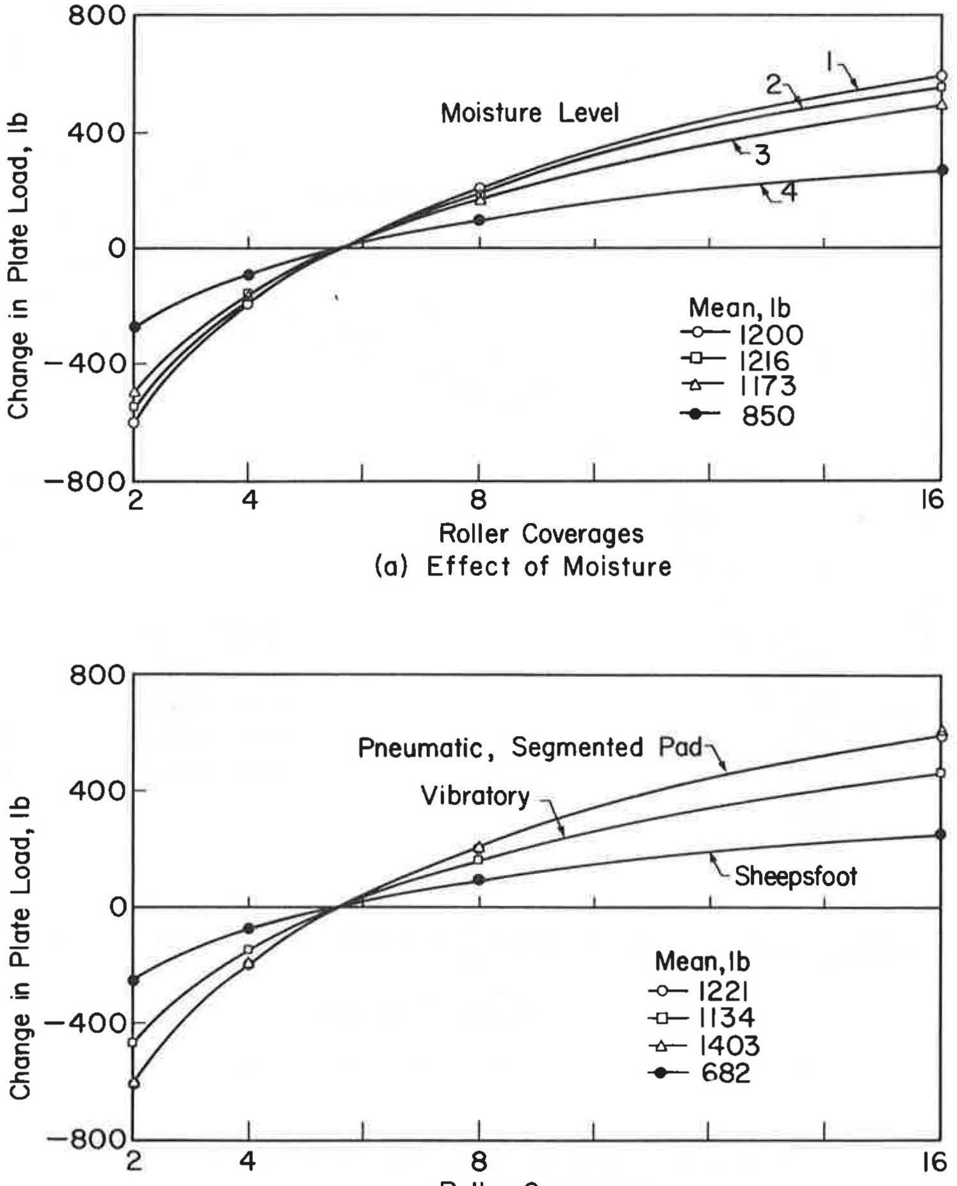


Figure 7. Average bearing plate growth curves for moisture level and compaction equipment.

ture levels and the highest moisture level had the smallest change. The trend was an increase in the magnitude of the change from moisture level 1 to 3 and then a decrease for moisture level 4 (Fig. 8). These differences were accentuated for the 6-in. lift thickness and decreased for the 12-in. thickness, giving an MT joint effect. The same trends generally held for all soils except the silt in which case the trend was inverted; i. e., the magnitude of the change decreased from moisture level 1 to 3 and then increased again for moisture level 4. In all cases the seismic velocity was still increasing after 16 coverages, except for the sheepsfoot roller at the highest moisture content. In this case the velocity continued to decrease beginning with coverage 2.

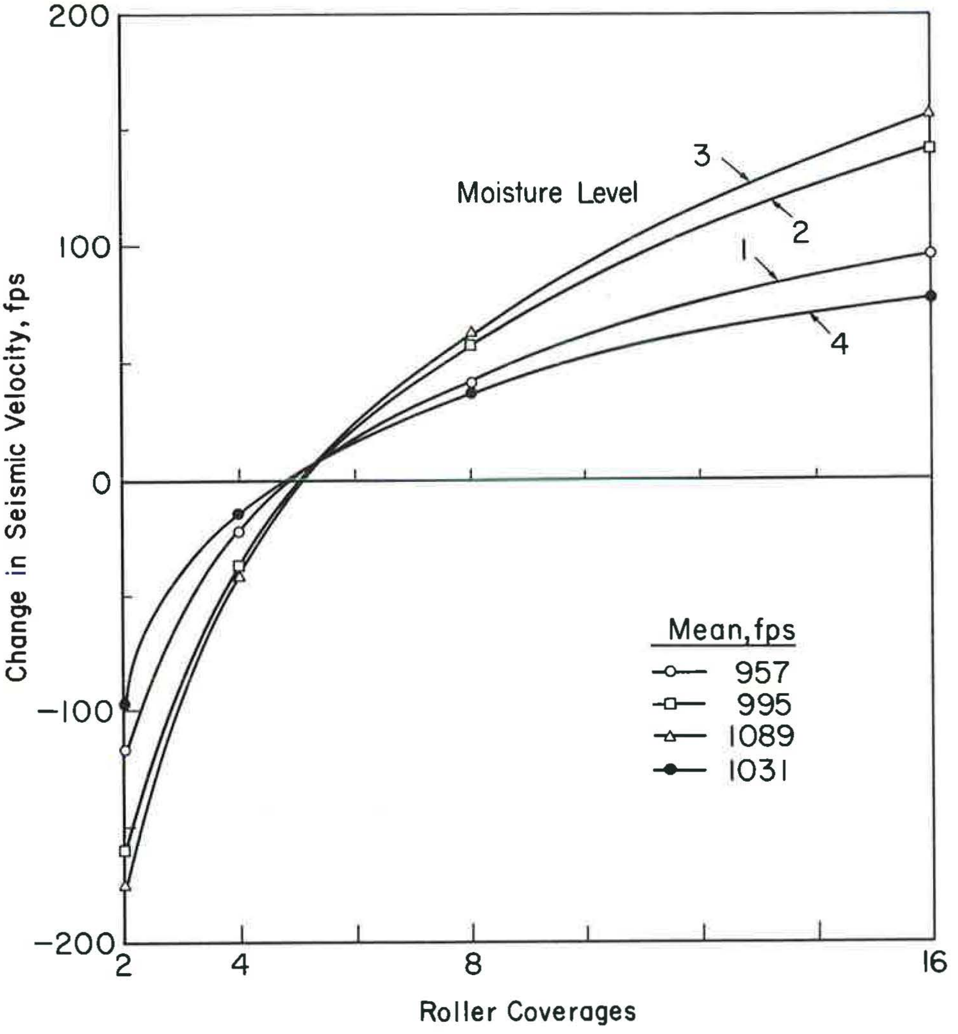


Figure 8. Average seismic velocity growth curves for moisture level.

MOISTURE-DENSITY-STRENGTH RELATIONSHIPS

Standard (T-99) and modified (T-180) Proctor compaction tests were performed in the laboratory on samples of soil taken from the stockpiles used for the field studies. In addition, a T-180 test was performed on a sample from each test section taken after mixing and just prior to the first coverage of the roller. These samples were compacted at the same moisture content as the test section and involved the identical preparation procedures. The average results from the field Proctor tests are compared in Figure 9 with the peak points from the laboratory tests.

The four subgrade soils have distinctly different moisture-density-strength characteristics. The field Proctor dry densities (T-180) lie midway between the T-99 and T-180 values obtained in the laboratory for the clay, silty clay and silty sand and gravel. The field values for the silt correspond approximately to the T-99 values from the laboratory tests. The optimum moisture contents appear to occur at about the same percent saturation as in the laboratory tests. The CBR values from the field T-180 tests correspondingly lay in a range midway between those for the laboratory T-99 and T-180 tests (not shown in Fig. 9), as would be expected considering the relationship of

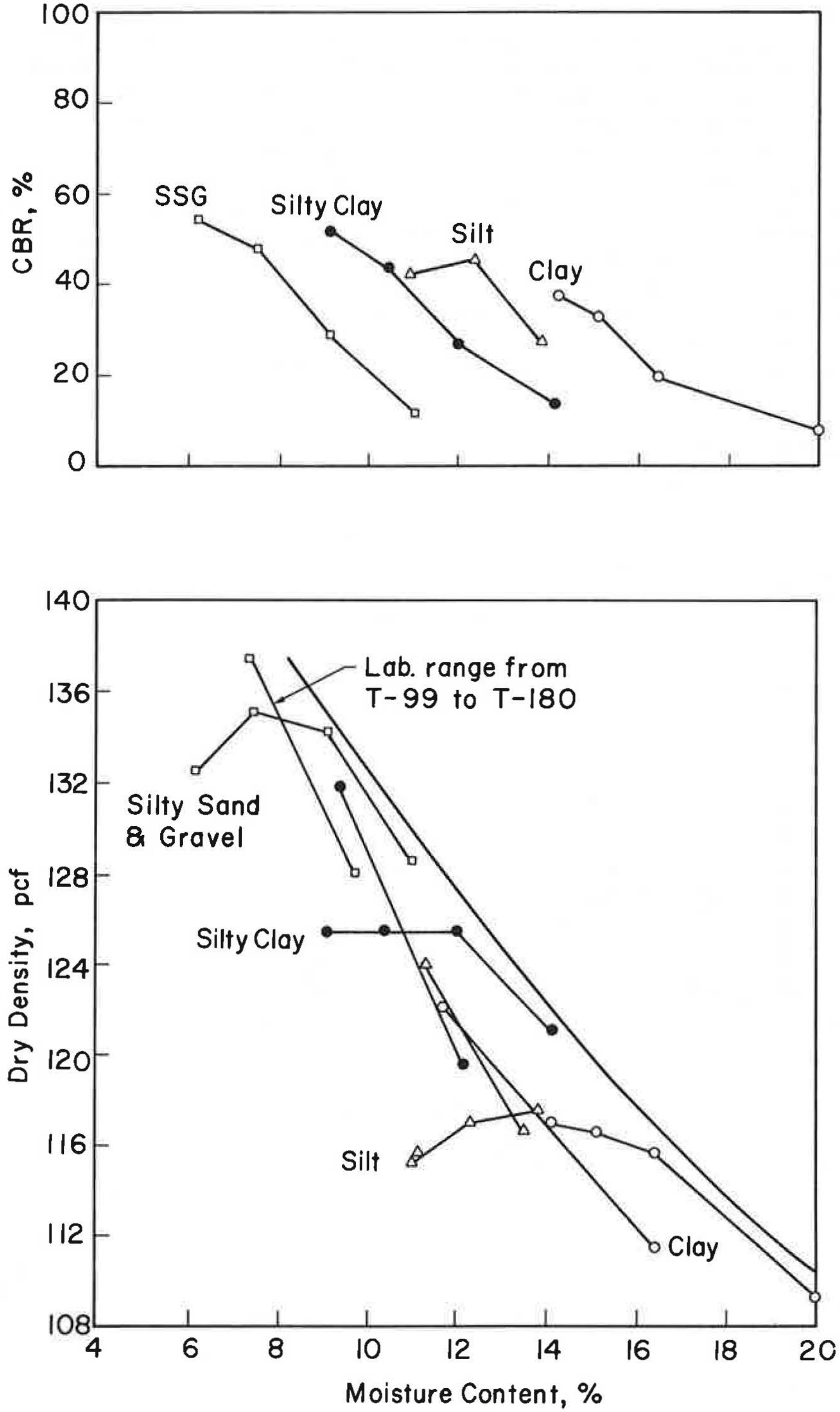


Figure 9. Moisture-density-CBR relationships from field modified Proctor tests.

the dry densities. However, the field CBR curves appear to be shifted toward higher moisture contents relative to the laboratory values than might be expected, based on magnitude of the related density alone.

An examination of the individual data from which the average values in Figure 9 were obtained showed that the discrepancy between the field and laboratory results could be explained to a large extent by the averaging process used. The analysis assigns all values of moisture content and dry density into four groups, one for each level of moisture in a lift. However, the actual values of moisture in each level varied enough between lifts to overlap those in other levels. Therefore, when each level is averaged, because of the concave downward shape of the moisture-density curves the resulting curve will be on the low side of the range of data. The analysis of variance model used needs further study in an attempt to find a means of overcoming this limitation. It is the field data in the form shown in Figure 9 which should be used for comparison with the results on the lifts, because both sets of data were analyzed using the same method.

The average moisture-density curves from the compacted lifts for each of the four soils are compared with the corresponding field T-180 curves in Figure 10. The lift

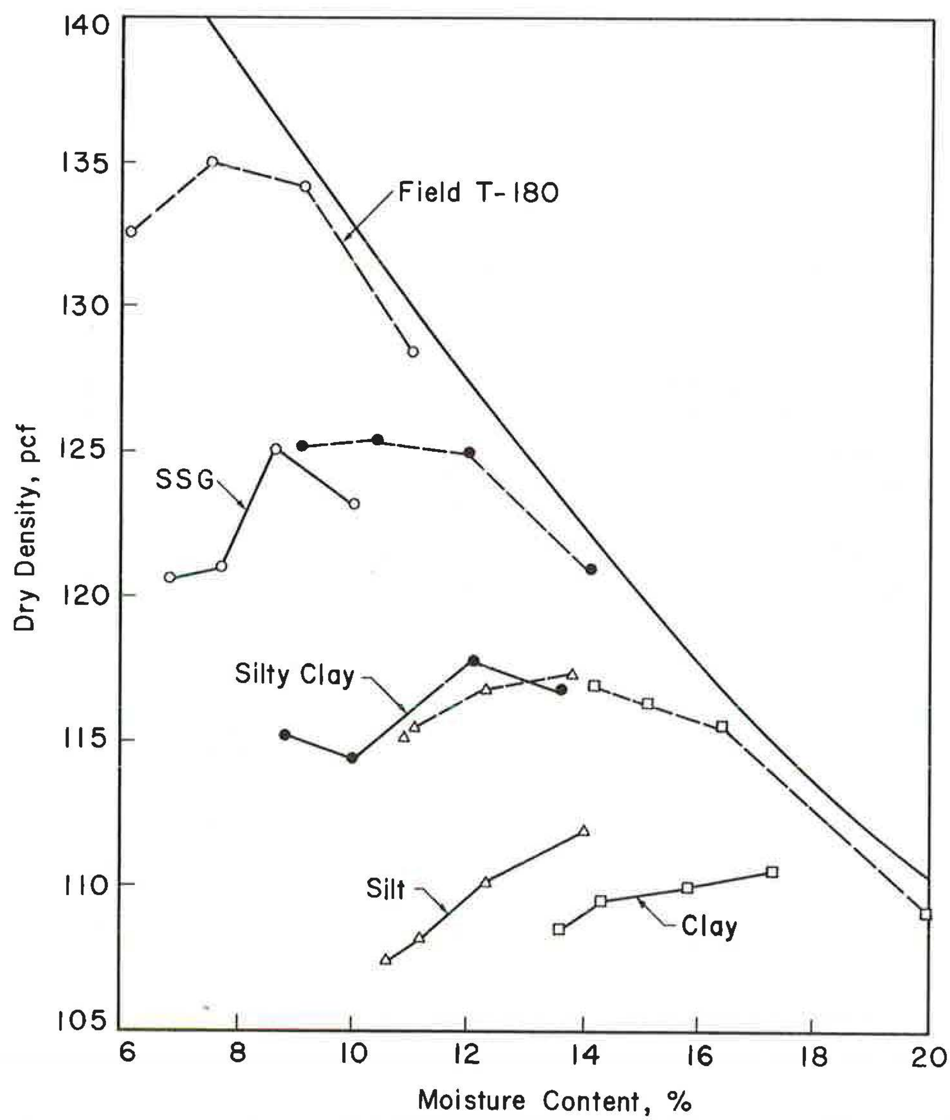


Figure 10. Average moisture-density relationships for each soil from compacted lifts compared with field Proctor tests.

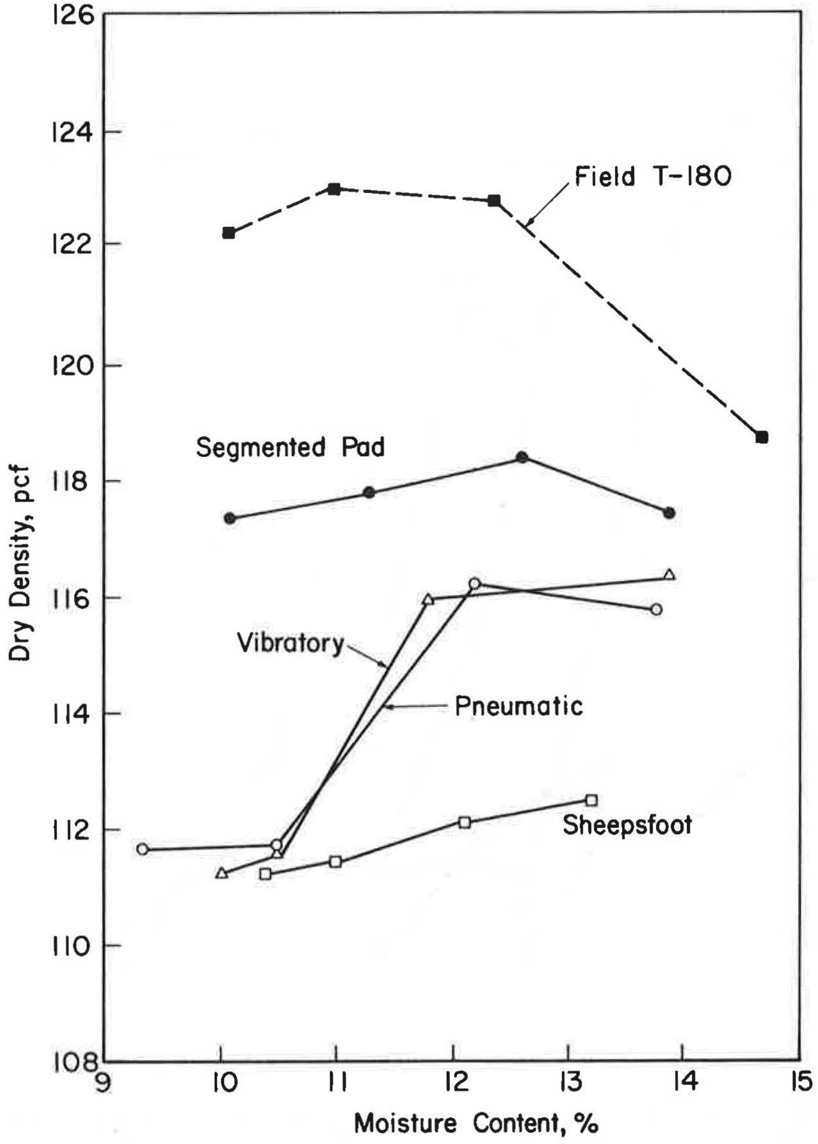


Figure 11. Average moisture-density relationships for each compactor.

curves appear to lie primarily on the dry side of optimum for the average conditions involved, and the average dry densities are substantially below those from the T-180 tests.

The moisture-density curves for each compactor averaged for all other conditions are shown in Figure 11. These curves confirm the dry side compaction for all rollers. The biggest change in dry density with moisture level occurred with the pneumatic and vibratory rollers.

The field CBR values for each soil as a function of moisture content are compared with the corresponding values from the field Proctor tests in Figure 12. The Proctor values are much higher than the values from the compacted lifts at the low end of the moisture range, and converge to similar values at the wet end of the range. This is the same manner as the CBR curves would be related for two different compactive

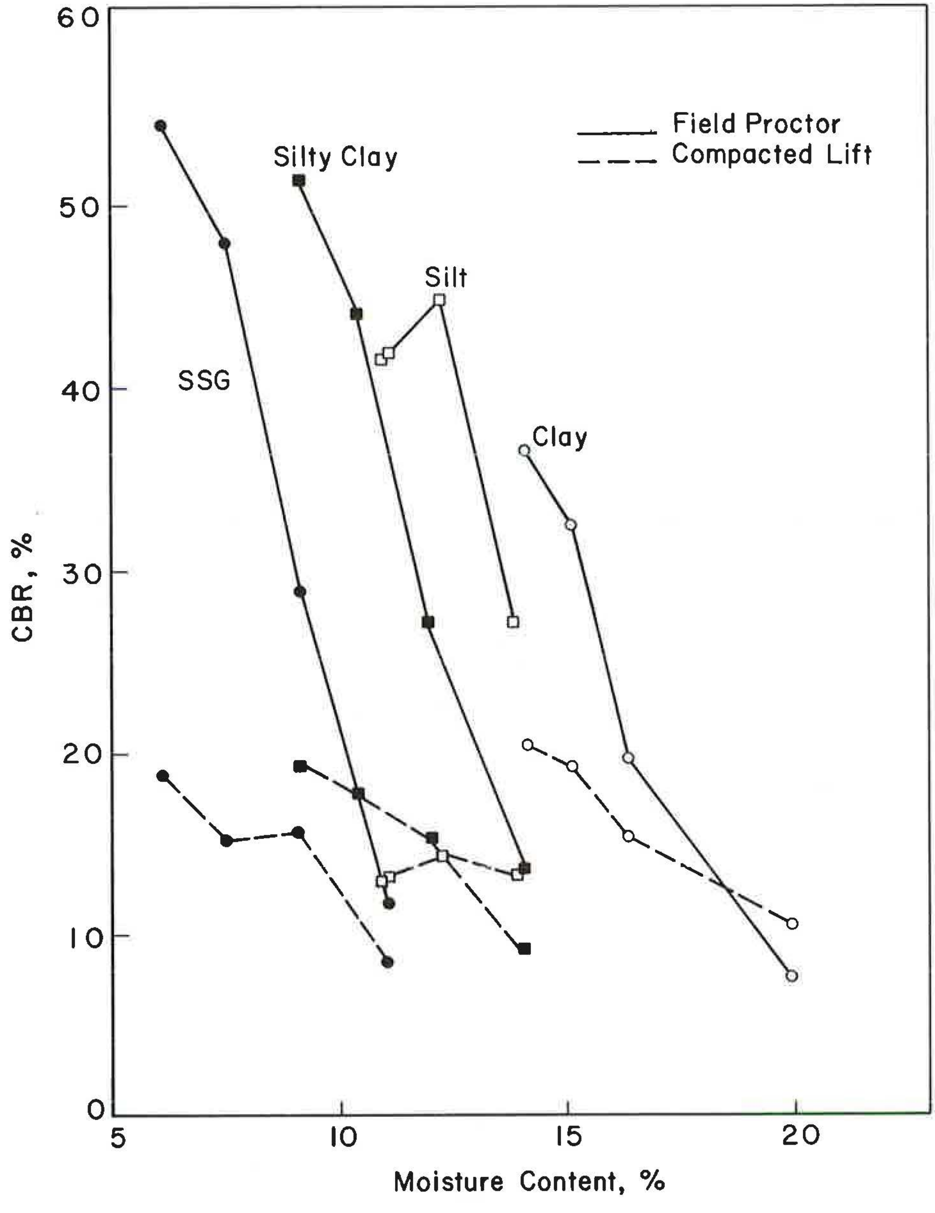


Figure 12. Comparison of field CBR on lifts and CBR from field Proctor tests for each soil.

efforts in the same soil. The magnitude of the difference is approximately that which would be expected on the basis of the difference between the corresponding densities (Fig. 10). The resemblence in shape between the pairs of curves is evidence of similarity in the compaction effects of the rollers and the Proctor hammer.

Previous discussion has dealt with average conditions. Comparisons can also be made for any combinations of the independent variables by superimposing the effects of each upon the average. In Table 4, the maximum dry densities based on the nuclear measurements are listed for each soil and compactor combination. They were obtained by adding to the average values for each SE combination after 16 roller coverages the increases caused by the most favorable compactive effort, lift thickness and moisture

TABLE 4

MAXIMUM COMPACTION FOR EQUIPMENT-SOIL COMBINATIONS

Compaction Equipment	Soil	T-180	T-99 (Estimated)		Maximum Dry Density (pcf)	Percent T-180	Percent T-99 (Estimated)
Pneumatic	Clay	117	107		118	101	110
	Silty clay	126	114		122	97	107
	SSG	135	126		127	94	101
	Silt	118	110		115	97	105
				Average	120	97	106
Vibratory	Clay	117	107		111	95	103
	Silty clay	126	114		119	95	104
	SSG	135	126		128	95	101
	Silt	118	110		112	95	102
				Average	117	95	103
Segmented pad	Clay	117	107		119	102	111
	Silty clay	126	114		125	99	110
	SSG	135	126		130	96	103
	Silt	118	110		119	100	108
				Average	123	99	108
Sheepsfoot	Clay	117	107		109	93	102
	Silty clay	126	114		116	92	102
	SSG	135	126		120	89	95
	Silt	118	110		111	94	101
				Average	114	92	100

level in each case. The maximum dry densities from the field T-180 tests were obtained from Figure 9. An estimate of the corresponding T-99 values was made by subtracting the differences observed in the laboratory Proctor tests. These values were used to compute the maximum dry density in percent of T-99 and T-180 for the compacted lifts.

The percent of T-180 obtained ranged from 89 to 102, the compactor order with respect to increasing values being sheepsfoot, vibratory, pneumatic and segmented pad. This ranking was essentially the same for all four soils, although the magnitude of the differences between rollers changed. The estimated percent of T-99 ranged from 95 to 111 with the compactor ranking remaining the same as for T-180. The same computations for the average dry densities for each roller give as percent T-180 the values 90, 92, 92 and 95 for the sheepsfoot, vibratory, pneumatic and segmented pad rollers, respectively. For percent T-99 the corresponding values are 98, 100, 100 and 103. Therefore, the average compaction is equivalent to T-99 and the ranking is the same as that for maximum dry density, except that under average conditions the pneumatic and vibratory rollers provide the same results.

SUMMARY AND CONCLUSIONS

This paper dealt with the properties of compacted soils based on observations from field tests in which the soil type, moisture content, lift thickness, compaction equipment and compactive effort were the main parameters varied. In view of the nature of the field test program, it is believed that the conclusions will have direct application to construction practice. Only the major effects could be detected from the resulting data because of the large variability encountered in the tests, principally as a result of moisture control difficulty. The behavior which could be observed will thus be pertinent to construction operations and those details which could not be distinguished because of the variability are probably not of practical significance. The test plan was based on a statistical model which permitted separation of real effects from random variability. An examination of appropriate field measurements verified the accomplishment of this objective.

The range of moisture contents selected bracketed the T-99 (standard Proctor) and T-180 (modified Proctor) values for each soil. The results showed that the average test conditions produced a level of compaction equivalent to the T-99 effort; thus, the measured properties represent behavior more on the dry side of optimum than on the wet side. Further study of the data should lead to a better understanding of effective compactive effort for a wide variety of compactor types. This is a subject which is not adequately understood at present, especially for vibratory rollers, and limits the ability to predict the relative performance of different field compaction equipment.

The observed properties of the field compacted soils appeared similar to those exhibited by laboratory compacted specimens. For the range of conditions involved, moisture was by far the most significant factor influencing the measurements. Next was the soil type and then in descending order of importance were compaction equipment, lift thickness and compactive effort. However, the relative importance of each of these parameters depended a lot on the specific combinations considered. There were no significant interactions between soil, lift thickness and compactive effort, and thus the effect of any one of these three parameters did not change with change in the others. Moisture and thickness had little interaction as well, leaving compaction equipment as the only parameter whose effect changed with a change in lift thickness. Another important observation was that the relative effectiveness of each roller did not change appreciably with change in soil type.

Increasing lift thickness from 6 to 12 in. caused a decrease in density of up to 6 to 8 pcf for the pneumatic and segmented pad rollers. No significant effect was observed for the vibratory and sheepsfoot rollers. The same trends were observed for the bearing plate, seismic and CBR measurements. The increase in compactive effort for the pneumatic and segmented pad rollers caused the largest increase in the measured properties. The change with the vibratory and sheepsfoot rollers had little effect. It will be recalled that the single-lift test section tended to be an unfavorable factor for the sheepsfoot roller.

Superimposed upon all of the foregoing effects, which are based on a constant number of roller coverages, is the effect produced by a change in the number of coverages. As a general rule, the magnitude of the measured properties increased with coverages, but in decreasing amounts. Only for wet density was there evidence of a leveling off of the growth curves in less than the 16 coverages considered. However, in the majority of cases wet density was increasing at a significant rate after four coverages and continued to increase over the entire range with as much as 3 to 5 pcf change from 8 to 16 coverages. When maximums were reached they occurred after 8 coverages.

The plate load and penetration resistance measurements generally showed no tendency to level off within 2 to 16 coverages, and half of the total increase in this range usually occurred after 6 coverages. The seismic velocity growth curves were intermediate between these and the wet density curves, but in all except a few cases exhibited no leveling off up to 16 coverages.

As comprehensive as this study has been there are still a number of important factors which have not been considered. Among them are foundation conditions, multiple layer compaction, long-term environmental influences, and roller speed. In addition, considerable analysis can still profitably be done with the data already collected. The statistical model should be further studied to provide a means of incorporating moisture as a continuous variable, and to include physically meaningful coefficients representing effective compactive effort and relationships between moisture and the measured properties. Field test programs should be a continuing effort because they provide direct application to practical field problems as well as an opportunity to apply fundamental knowledge gained through basic research and, as a result, serve to bridge the gap between theory and practice.

ACKNOWLEDGMENTS

The authors would like to thank the following organizations which made this study possible and contributed to its success: the Bureau of Public Roads, represented by T. F. McMahon; the states of Indiana, Iowa, Kentucky, Louisiana, Massachusetts, Minnesota, Mississippi, Montana, New Mexico, Ohio, Rhode Island, Utah, West Virginia and Wisconsin, and the Commonwealth of Puerto Rico, all represented by a steering committee led by C. R. Hanes of the Ohio Department of Highways; the compaction equipment manufacturers, represented by M. J. Trainor; and the George J. Beemsterboer Construction Company, represented by T. Beemsterboer, who was the subcontractor for the field work. Appreciation is also expressed to Lane-Wells Co., Minnetech Labs, Inc., and Nuclear-Chicago Corp., who provided instruments for the study.

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