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Opportune Landing Site Program

Opportune Landing Site CBR and Low-Density Laboratory Database

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Rosa T. Affleck, and Wendy L. Wieder

May 2008

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Final report

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Abstract: Laboratory CBR (California bearing ratio) tests were performed on soils obtained from Opportune Landing Sites (OLS) in California, Texas, and Indiana. Initial CBR samples were prepared using standard American Society for Testing and Materials (ASTM) methods (i.e., compaction effort). Standard laboratory methods rarely reproduce in-situ density, moisture, and CBR values and therefore do not accurately represent the complete range of these values measured in the field. Because the OLS program focuses on natural unprepared sites for use as landing zones, a repeatable method of reproducing in-situ strength CBR values in the laboratory was necessary. By reducing the compaction effort on the laboratory samples, density and moisture regimes found in field conditions were more closely matched. Various compaction techniques were used to prepare consistent, low-density samples for CBR measurements. A companion study was performed for a detailed analysis on the effect of fine-grained soil particles on CBR values. A well-graded (SW) and poorly graded (SP) sand were used as the base material. A clay (CL) and silt (CL-CH) were added to the sand in varying proportions. CBR samples were prepared with these blended soils using both standard and low-density compaction methods.

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Nomenclature

ASTM	American Society for Testing and Materials
C	USCS letter symbol for soil group clay
CBR	California bearing ratio
CI	Cone index
CRREL	Cold Regions Research and Engineering Laboratory
DoD	Department of Defense
DTED	Digital terrain evaluation data
ERDC	United States Army Engineer Research and Development Center
FASST	Fast All-season Soil STrength model
FM	Field Manual
ft	Foot
G	USCS letter symbol for soil group gravel
GSL	Geotechnical and Structural Laboratory
H	USCS letter symbol for soil characteristic high plasticity (LL over 50)
in.	Inch
JRAC	Joint Rapid Airfield Construction
L	USCS letter symbol for soil characteristic low plasticity (LL under 50)
lb	Pound
LL	Liquid limit
M	USCS letter symbol for soil group silt

NCHRP	National Cooperative Highway Research Program
O	USCS letter symbol for soil characteristic organic (silts and clays)
OLS	Opportune Landing Site
P	USCS letter symbol for soil characteristic poorly graded
Pcf	Pounds per cubic foot
PI	Plasticity index
PL	Plastic limit
psi	Pounds per square inch
Pt	USCS letter symbol for soil characteristic organic (peat)
S	USCS letter symbol for soil group sand
TM	Training Manual
TO	Theater of Operations
US	United States
USACE	United States Army Corps of Engineers
USAF	United States Air Force
USCS	Unified Soil Classification System
W	USCS letter symbol for soil characteristic well-graded

Preface

This report was prepared by Larry S. Danyluk, Dr. Sally A. Shoop, and Rosa T. Affleck, Force Projection and Sustainment Branch, Cold Regions Research and Engineering Laboratory (CRREL), US Army Engineer Research and Development Center (ERDC), Hanover, New Hanover, and by Dr. Wendy L. Wieder, Consultant, Science and Technology Corporation, Hanover, New Hampshire.

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At the time this work was performed, Colonel Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Current United States (US) Army and Air Force (USAF) procedures for the planning and design of airfields in Theater of Operations (TO) entail several steps (US Army and USAF 1994). For an unimproved or expedient-surfaced airfield, proposed sites of the proper size and geometry must be located, the design aircraft with its associated gross weight selected, and in-place soil strength measured. For most military applications, the soil's California bearing ratio (CBR) is used as an empirical measurement of shear strength, one of the two failure mechanisms of soil under load (i.e., bearing capacity) along with settlement (US Army and USAF 1994). CBR, obtained from either laboratory or field testing, is used with empirical curves to determine whether the soils at the site can support aircraft operational loads.

To date, only an advanced contingent of military personnel on the ground, performing standard field soil bearing tests, have been able to provide the measurements or soil samples necessary to determine CBR. In non-hostile environments, specially trained civil engineering personnel conduct these evaluations. In hostile situations, combat control teams conduct the evaluations under clandestine conditions. There are several limitations to the current methods, including compromising the location itself, and danger to personnel performing the evaluations in hostile environments.

The Opportune Landing Site (OLS) program, a joint industry/Department of Defense (DoD) initiative, is intended as a military planning tool to help select candidate landing sites, determine soil type, and infer the soil CBR to evaluate a site's potential to support military airlift operations. Within the OLS program, efforts are under way by Boeing to develop mapping software that uses commercially available LANDSAT imagery to remotely locate unimproved landing sites in natural terrain. Currently available LANDSAT imagery can identify areas that are sufficiently flat, and free of heavy vegetation, obstacles, and surface water, to allow airlift operations, soil and weather conditions permitting.

Once a potential site has been identified, the second module of the OLS program, also under development by Boeing, determines the soil type

based on the pixelated satellite imagery and digital terrain evaluation data (DTED).

Finally, under the third module of OLS software, CRREL is using the Fast All-Seasons Soil STate (FASST) model (Frankenstein and Koenig 2004), with the inputs of soil type and measured or modeled weather data, to predict the soil moisture content and infer CBR. CBR is in turn used to evaluate the trafficability of the site by a specific aircraft. Together, the modules of the OLS program would eliminate the need for on-ground reconnaissance to locate potential landing sites prior to aircraft operations.

1.1 Background

The OLS bearing capacity inference segment is based on a historical database of soils, and their engineering properties, from throughout the world. Because the USAF design standard for bearing capacity is CBR, obtaining actual CBR data for many soil types augments the database and allows the OLS program to be widely applicable to global soils using USAF design methods.

There are several existing methods for predicting CBR values for soils (Semen 2006):

- CBR values by soil type based on the Unified Soil Classification System (USCS). From the literature, Semen presents a table of CBR values determined historically for specific soil types as defined by the USCS.
- Mechanistic-Empirical Design for New and Rehabilitated Pavement Structures as developed under the National Cooperative Highway Research Program (NCHRP) (2004) uses a simple regression approach to predict CBR based on grain size characteristics for non-plastic soils, and grain size and plasticity index for plastic soils.
- Soil strength “signature” concept combines laboratory results from CBR and standard moisture-density tests (known as Proctor curves) to provide a relation between CBR, compaction, and moisture content.

- Joint Rapid Airfield Construction (JRAC) program in progress is developing a prediction model for CBR based on moisture content and compaction levels, for different USCS soil types. This approach is also based on regression analysis.
- Several site-specific or specialized prediction models, where soils from a specific location or region have been sampled and tested to determine CBR relationships specific to those soils. These approaches, though developed to work in specific locations, also may have application in a global database and prediction model. The methods developed involve
 - o field moisture content,
 - o optimum moisture content,
 - o soaked CBR (laboratory),
 - o maximum dry density,
 - o soil suction,
 - o angle of friction (ϕ),
 - o field dry density,
 - o plasticity index,
 - o and liquid limit.

Within the OLS program there are several other efforts to infer or model CBR values for soils. Semen (2006) is using a machine learning approach, k-nearest neighbor, with existing CBR values from a variety of soils and sites to predict CBR. Shoop et al. (in preparation) are using regression analysis to correlate field CBR with cone index (CI) measurements, as CI values are more numerous in the OLS soils database. Additional correlations of CBR with soil moisture (and other properties), along with a theoretically based prediction scheme also using CI (Grant and Mason in press) are documented in Ryerson et al. (in preparation).

1.2 Scope

As a complement to the work of Semen (2006) and others to provide the greatest amount and variety of CBR data for use in the OLS program, this report focuses on determining CBR values in a controlled laboratory environment for a variety of soils and soil conditions. It is hoped that laboratory CBR values will not exhibit as much variation within a single soil or soil type as seen in field CBR values so far obtained for the OLS soils database (Shoop et al. in preparation), and will provide additional data and insight for soil strength inference models being investigated by others in the OLS program.

In addition to increasing the CBR database for a variety of soils and soil conditions with laboratory values, this effort also looks at the effect of compaction on CBR. In-situ soils typically have much lower density than soils prepared in the laboratory for CBR tests, or those mechanically compacted to provide a traffic surface. In order for the OLS program to select usable sites for aircraft operations, it must also be able to eliminate sites with in-situ soils of insufficient density and strength. Therefore, the OLS database must be populated with soils with a range of densities typical of undisturbed natural conditions. This aspect of the effort included applying new methods to reliably and repeatedly prepare low-density samples.

Another aspect of the work was to simulate variation in moisture content, as it is known that in-situ soil strength may vary significantly with moisture content, and the OLS software may use moisture content to infer CBR values. A potential landing site that may be acceptable for use after long periods of dry weather can quickly become unsuitable after a precipitation event. The presence of groundwater also can contribute to decreased soil strength, and also was examined in this effort.

The final aspect of this laboratory effort was to look at the effect of the percentage of fines on soil strength and density. As prediction and modeling efforts for soil strength parameters have continued under the OLS program, consistent values of CBR, and consistent correlations of CBR and CI, or CBR with moisture content, for sandy soils have been difficult to obtain. One theory for the inconsistency of these data and relationships is variation in moisture content, as investigated above. Another theory is that the percentage of fines in these soils significantly affects their strength characteristics.

It is not within the scope of this work to develop equations or models to infer CBR from soil properties determined during the testing (i.e., moisture content, dry density, and fine content) This work is being pursued by others as discussed in Section 1.1.

2 California Bearing Ratio Test

The CBR test was originally developed by O.J. Porter for the California Highway Department during the 1920s. It is a load-deformation test performed in the laboratory or the field; results are then used with an empirical design chart to determine the thickness of flexible pavement, base, and other layers for a given vehicle loading. Though the test originated in California, the California Department of Transportation, and most other highway agencies, have abandoned the CBR method of pavement design for the Hveem stabilometer and other methods (Oglesby and Hicks 1982). In the 1940s the US Army Corps of Engineers (USACE) adopted the CBR method of design for flexible airfield pavements and the USACE and USAF design practice for surfaced and unsurfaced airfields is still based on CBR (US Army and USAF 1994).

CBR may be performed either in the laboratory, usually with a recompact sample, or in the field. Because of typical logistical and time constraints, the laboratory test does not lend itself to use for contingency road and airfield design. In-place CBR tests are also time-consuming to run and are usually impractical for use in the TO (US Army and USAF 1994). To address the concerns with the standard CBR tests, the military have adopted other tools more suited for field operations. The airfield cone penetrometer and the dual-mass dynamic cone penetrometer (DCP) are most typically used in the field, and correlations are provided to translate their measurements into CBR values for use in design (US Army and USAF 1994).

The laboratory CBR test method is defined by ASTM D 1883-05 *Standard Test Method for CBR of Laboratory Compacted Soils* (2005). Laboratory CBR tests were performed by measuring the penetration resistance of a 1.954-in.- (49.63-mm-) diameter, 3-in.² (7.62-mm²) end area, cylindrical steel piston advanced into a soil sample at a rate of 0.05 in. (1.27 mm) per minute. The soil sample is contained in a standard 6-in.- (152.4-mm-) diameter by 7-in.- (177.8-mm-) high mold, with the standard surcharge ring weighing ten pounds placed on the top of the sample to provide material containment.

The reaction force, in pounds per square inch (psi), is measured at increments of 0.025 in. (0.64 mm) until a total penetration of 0.500 in. (12.70 mm) is reached. To determine the CBR value, the reaction force measured at 0.100-in. (2.54-mm) penetration is compared to standardized value of 1,000 psi (6.9 MPa). This represents the resistance of a high-quality, well-graded crushed limestone gravel with 3/4-in. maximum aggregate-sized particles. The value of the force measured in the test is divided by the standardized value (1,000 psi), and then multiplied by 100, to yield an index value. This value is reported as the CBR of the soil, in percent.

Various compaction methods were used to prepare the CBR samples and are discussed in Section 3.2 below. CBR tests were performed on both soaked and unsoaked samples. Soaked samples were immersed in water for a minimum of 96 hours according to procedures outlined in ASTM D 1883-05 (2005).

3 Laboratory Program

3.1 Soils

Twenty soils were selected for the test program. Table 1 presents the soils, their source locations, and some of their basic descriptive properties. The grain size analysis curves for each soil are presented in Section 3.4 and Appendix A. Five of these soils—Cinci (CL), Cobb (CL), El Centro (SW-SM), Ford Farm (CL-ML), and Fort Bliss (SM)—were also investigated as part of the OLS field site evaluation program (Barna et al. in preparation, Affleck et al. in preparation a and b). The terms in () are the USCS soil classifications, defined in the nomenclature (page vii). The other fifteen soils were blended in the laboratory using different combinations of four soils: SP, SW, CH, and CL. The two types of soil combinations included either SP or SW as base soils combined with CH or CL soils as an additive, in varying percentages, to obtain a new soil gradation.

3.2 Compaction Effort

3.2.1 Standard Compaction Procedures

CBR samples were compacted according to one of three standard methods. The three methods used were 1) ASTM D 1557-02 Modified Proctor Method D (ASTM 2007a), 2) ASTM D 698 Standard Proctor Method C (ASTM 2007b), and 3) USACE Standard CE-12 (US DoD 1964). A summary of compaction procedures is shown in Table 2. All specimens were compacted using an automated CBR compaction device (Durham S-235 Automatic Soil Compactor).

It should be noted that during the preparation of some of the ASTM Standard Proctor Method C samples, the hammer used weighed slightly more than specified in the ASTM procedure. This resulted in greater compaction of the sample, influencing the density and CBR values. The heavier hammer produced compaction energy of 13,795 ft-lb/ft³, versus the 12,320 ft-lb/ft³ of compaction delivered by the standard hammer, an increase of approximately 12%.

Table 1. Laboratory CBR soils.

Soil name	Source	Soil classification	Base soil	Additive soil		Specific gravity	Liquid limit	Plastic limit	Plasticity index
				% by weight	Soil type				
Cinci	SEPAC*, IN	CL	—	—	—	2.67	32	17	15
Cobb	SEPAC, IN	CL	—	—	—	2.61	28	16	12
El Centro	El Centro, CA	SW-SM	—	—	—	2.65	NP	NP	NP
Ford Farm	Dupont, IN	CL-ML	—	—	—	2.63	24	18	6
Fort Bliss	Fort Bliss, TX	SM	—	—	—	2.63	NP	NP	NP
SP	Hartland, VT	SP	—	—	—	2.74	NP	NP	NP
SW	Hartland, VT	SW	—	—	—	2.73	NP	NP	NP
CH**	Vicksburg, MS	CH	—	—	—	2.74	72	27	45
CL*	Dover, NH	CL	—	—	—	2.71	29	19	10
SP5CH	Hartland/Vicksburg	SP-SM	SP	5	CH	2.7	NP	NP	NP
SP25CH	Hartland/Vicksburg	SC	SP	25	CH	2.7	44	18	26
SP45CH	Hartland/Vicksburg	SC	SP	45	CH	2.7	59	25	34
SW5CH	Hartland/Vicksburg	SW-SM	SW	5	CH	2.7	NP	NP	NP
SW25CH	Hartland/Vicksburg	SC	SW	25	CH	2.7	43	16	27
SW45CH	Hartland/Vicksburg	SC	SW	45	CH	2.7	57	23	34
SP9CL	Hartland/Dover	SM	SP	9	CL	2.72	NP	NP	NP
SP23CL	Hartland/Dover	SC-SM	SP	23	CL	2.73	24	17	7
SP35CL	Hartland/Dover	SC-SM	SP	35	CL	2.73	22	16	6
SW10CL	Hartland/Dover	SM	SW	10	CL	2.74	NP	NP	NP
SW30CL	Hartland/Dover	SM	SW	30	CL	2.71	22	17	5
SW40CL	Hartland/Dover	SC	SW	40	CL	2.71	27	19	8
SW60CL	Hartland/Dover	CL	SW	60	CL	2.67	28	18	10

* SEPAC (South East Purdue Agricultural Center)

** CH and CL soils were used only as additive soils; no CBR testing or density measurements were performed on these soils.

Table 2. Summary of standard compaction procedures.

Compaction effort	Mold diameter (in.)	Hammer weight (lb)	Drop height (in.)	Number of layers	Blows per layer	Energy (ft-lb/ft ³)
ASTM 698	6	5.5	12	3	25	12,320
ASTM 698*	6	6.16	12	3	25	13,795
ASTM 1557	6	10	18	5	56	56,000
CE-12	6	10	18	5	12	12,000
*Non-standard hammer weight						

Table 3 lists the number of samples prepared for each soil or soil combination for the standard compaction testing. Each set of samples at a given compactive effort was prepared at a range of moisture contents in an attempt to bracket the optimum moisture content, defined as the moisture content at which a given soil can be compacted to greatest density, and to provide additional data for use in CBR inference models including moisture content (Ryerson et al. in preparation). Approximately half of each sample set for a given soil was tested unsoaked, and half were tested soaked to investigate the effect of prolonged saturation on the soil strength.

Table 3. Sample preparation for standard compactive effort investigation.

Soil	Samples per compactive effort				Total samples
	12,320 (ft-lb/ft ³)	13,795 (ft-lb/ft ³)	56,000 (ft-lb/ft ³)	12,000 (ft-lb/ft ³)	
Cinci	—	11	12	12	35
Cobb	—	10	16	11	37
El Centro	—	9	—	10	19
Ford Farm	—	10	10	10	30
Fort Bliss	—	13	10	11	34
SP	—	10	—	10	20
SW	—	10	—	10	20
SP with CH combinations*	25	—	24	24	73
SP with CL combinations	—	30	—	30	60
SW with CH combinations	24	—	24	24	72
SW with CL combinations	—	41	—	41	82
* For soil combination samples, the total number of samples was prepared for each percentage of additive soil.					

3.2.2 Low-Density Compaction Procedure

Preparing samples with lower soil densities more in line with those of in-situ surface soils required a different compaction procedure than the standard methods described in Section 3.2.1. Standard laboratory compaction methods result in densities that are typically higher than undisturbed in-situ values, as these tests and resulting densities were developed as a means to evaluate the effectiveness of mechanically compacting soils in the field. Because the OLS program is interested in undisturbed field density values, a method to consistently compact soils at lower densities was developed.

Standard compaction methods were modified by varying hammer weight, hammer drop height, number of blows per layer, and number of layers. The reduced compaction effort (ft-lb/ft³) resulted in lower densities while still retaining a uniformly compacted soil specimen. Table 4 outlines the procedures used for low-density compaction. Compaction efforts higher than Low-Density Method 3 resulted in soil densities higher than those found at OLS field test sites. For compaction efforts less than Low-Density Method 1, it was visually obvious that the samples were not uniformly compacted throughout the soil profile. Note that these compactive energies are less than one-quarter of those used in even the lowest standard compactive effort within the ASTM test methods.

Table 4. Summary of low-density compaction procedures.

Low-density method	Mold diameter (in.)	Hammer weight (lb)	Drop Height (in.)	Number of layers	Blows per layer	Energy (ft-lb/ft ³)
1	6	6.16	12	2	6	985
2	6	6.16	12	3	6	1,474
3	6	6.16	12	3	12	2,956

Table 5 summarizes the samples prepared for each soil or soil combination for the low-density compaction effort testing. Each set of samples at a given compactive effort was prepared at a range of moisture contents that corresponded to values previously used in the standard compaction methods. These samples were tested only in the unsoaked condition because we expected soaked values to have little or no strength.

Table 5. Sample preparation for low-density compactive effort investigation.

Soil	Samples per compactive effort			Total samples
	985 (ft-lb/ft ³)	1,474 (ft-lb/ft ³)	2,956 (ft-lb/ft ³)	
Cinci	5	5	5	15
Cobb	5	5	5	15
El Centro	5	5	5	15
Ford Farm	5	5	5	15
Fort Bliss	5	5	5	15
SW10CL	4	4	5	13
SW30CL	5	5	5	15
SW40CL	5	5	5	15
SW60CL	3	3	3	9

3.2.3. Poured Sample Procedure

This procedure was developed to produce extremely low-density samples in the laboratory. Preliminary tests showed that in order to achieve the desired densities, the soil had to be relatively dry, with moisture contents of approximately 2–3% of dry soil weight. Samples with higher moisture contents tended to form voids when placed in the mold. The only way to remove these voids was by tamping, a form of compaction, and thus contrary to our goal.

In order to more accurately control moisture content and to accommodate the blending of the soil combinations (Section 3.4), specimens were prepared by adding water to oven-dried soil such that the final moisture content was, as stated above, between 2 and 3% by dry soil weight. The soil was thoroughly mixed, covered, and left to equilibrate for 24 hours. The following day, the soil was poured from a height of 7 in. into a 6-in.-diameter CBR mold with the collar attached. The collar was removed and the sample was trimmed to the height of the CBR mold with a straight edge. The specimens were then weighed and the unit weight of the soil was determined. Table 6 gives the number of samples prepared for each soil type or soil combination.

Table 6. Low-density poured samples.

Soil name	Number of samples
Cinci	3
Cobb	3
El Centro	4
Ford Farm	3
Fort Bliss	3
SP	3
SW	3
SP5CH	4
SP25CH	4
SP45CH	4
SW5CH	4
SW25CH	4
SW45CH	4
SP9CL	3
SP23CL	3
SP35CL	4
SW10CL	3
SW30CL	3
SW40CL	4
SW60CL	3

3.3 Soil Moisture Content

3.3.1 Variation of Moisture Content, Soaked and Unsoaked Tests

As stated in Section 3.2.1, standard compaction samples were prepared at a range of moisture contents with the intent of providing additional data to help quantify the relation between CBR and soil moisture. Samples were also tested both in soaked and unsoaked conditions.

3.3.2 Wetting and Drying Experiments

During the OLS field investigations, it was noted that some in-situ soils exhibited little or no strength when they became disturbed and had very low moisture contents. However, following a rain event, the soil regained some or all of its original strength. This effect of soil moisture was further investigated using the poured low-density samples. The following labora-

tory tests were designed as a controlled study on the impacts of wetting and drying on CBR.

After the poured samples were prepared, trimmed, and weighed, they were divided into four groups: 1) dry, 2) rain, 3) rain and dry, and 4) water table. For the dry sample the standard CBR test was performed immediately.

For the rain test, filter paper was placed on top of the sample as shown in Figure 1. The collar, along with a rubber “O” ring, was then bolted back on the mold and the sample was subjected to a “rain” event. Rain was simulated using a spray bottle as shown in Figure 2. A total of 500 mL of water was applied over a time span of one hour to simulate four separate precipitation events of approximately 0.25 in. After 24 hours, the collar was removed, any consolidation of the sample surface was measured, the mold and sample were weighed, surcharge load applied, the CBR test run, and the final moisture content of the sample determined.



Figure 1. Sample being prepared for “rain” conditioning.



Figure 2. Sample receiving “rain” conditioning.

A limited number of tests received multiple cycles of rain events followed by drying periods (those soils and soil combinations with four samples prepared, as listed in Table 6). The sample was subjected to rain, as stated above, followed by a one-week air-drying period. The process was repeated twice, with the last drying period being two weeks. The total test length was four weeks with three rain events. Again, the standard CBR test was then performed, and final moisture contents determined.

Water table samples were similar to soaked samples in that they were placed in a tub where the water level was kept to within one inch of the top of the soil sample. After 24 hours, the sample was removed from the tub and allowed to drain for one hour. The sample was then weighed, measured for surface subsidence caused by sample consolidation, the surcharge applied, and the CBR test completed. The final moisture content was then determined.

3.4 Percentage of Fines

The general effects of the percentage of fines on soil strength and/or density were investigated by varying the percentages by weight of fine material

added to two sandy soils. The base and additive soils' properties are listed in Table 7 and the grain size charts for each of the combinations are shown in Figures 1–6. Physical properties of the combination soils are given in Table 1. Samples made using the CH additive soil were prepared and tested at the Engineer Research and Development Center's (ERDC) Geotechnical and Structures Laboratory (GSL) in Vicksburg, Mississippi. All other samples, including all poured CH samples, were prepared and tested at ERDC's Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire.

Table 7. Soil properties of base and additive soils.

Soil name	Source	Base/ additive	USCS soil classification	LL	PL	PI	SG
SP	Hartland, VT	Base	SP	—	—	NP	2.74
SW	Hartland, VT	Base	SW	—	—	NP	2.73
CH	Buckshot clay Vicksburg, MS	Additive	CH	72	27	45	2.74
CL	Dover, NH	Additive	CL	29	19	10	2.71

Additive percentages were based on total mixed soil weight. For example, 100 lbs of “SW₅CH” contains 95 lbs of SW soil and 5 lbs of CH soil. All weights are based on oven-dried samples. Samples were prepared using oven-dried base and additive soils. Water was then added to the mix to obtain the desired moisture content. The mix was allowed to equilibrate for 24 hours and then compacted into a CBR sample. Table 3 indicates the number of samples prepared for each combination.

Low-density compaction efforts were used only for samples prepared from SW soil with the CL additive. These samples are listed in Table 5. Poured samples were prepared with all of the soil combinations, as listed in Table 6.

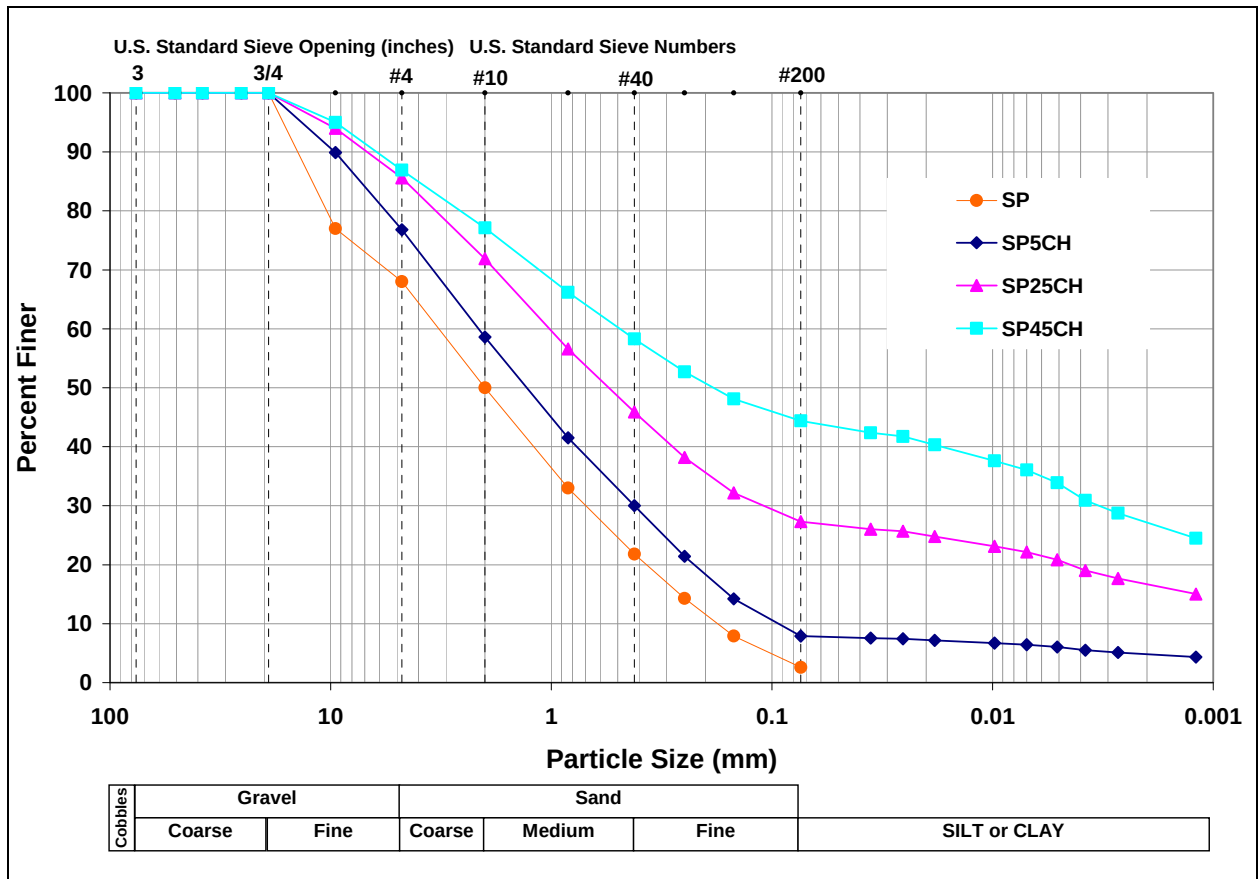


Figure 3. Grain size curves for SP and CH blended soils.

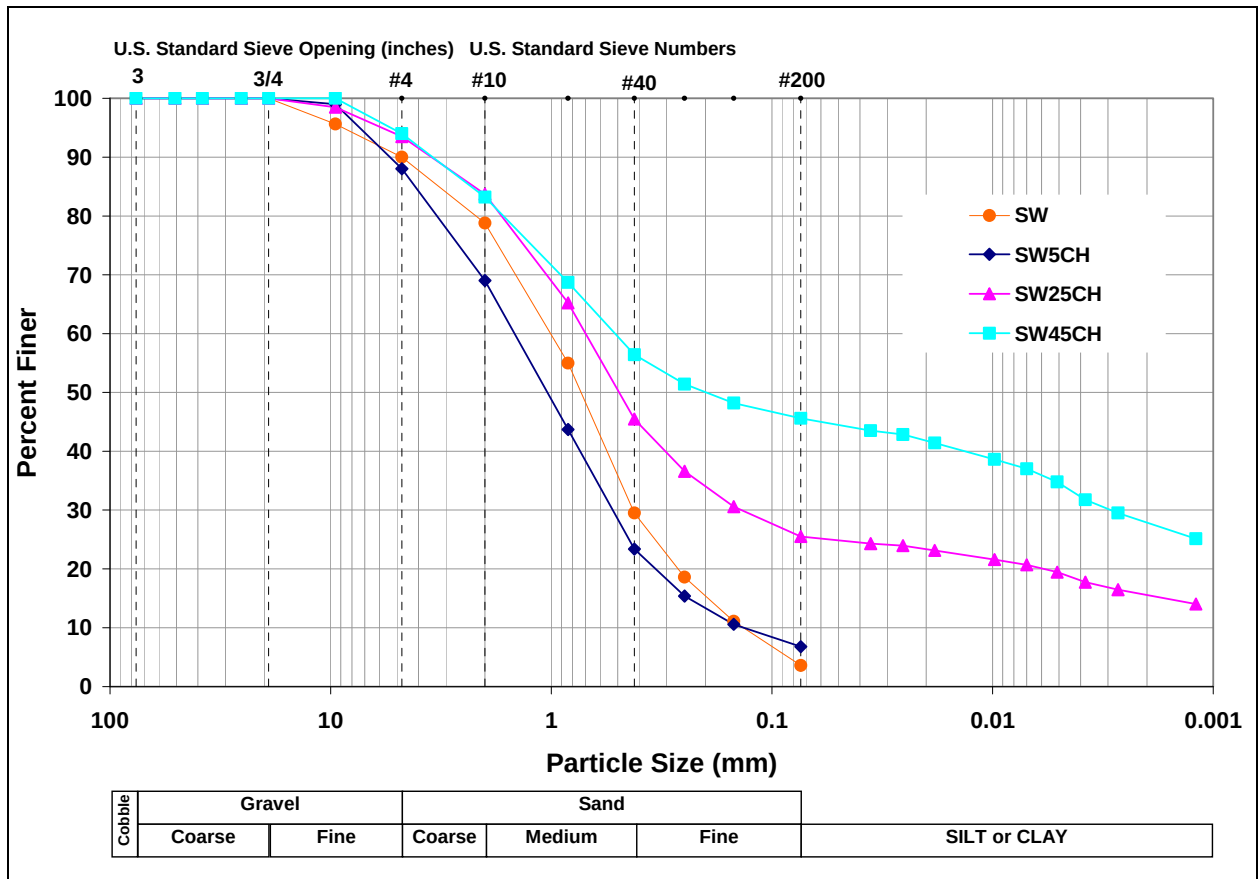


Figure 4. Grain size curves for SW and CH blended soils.

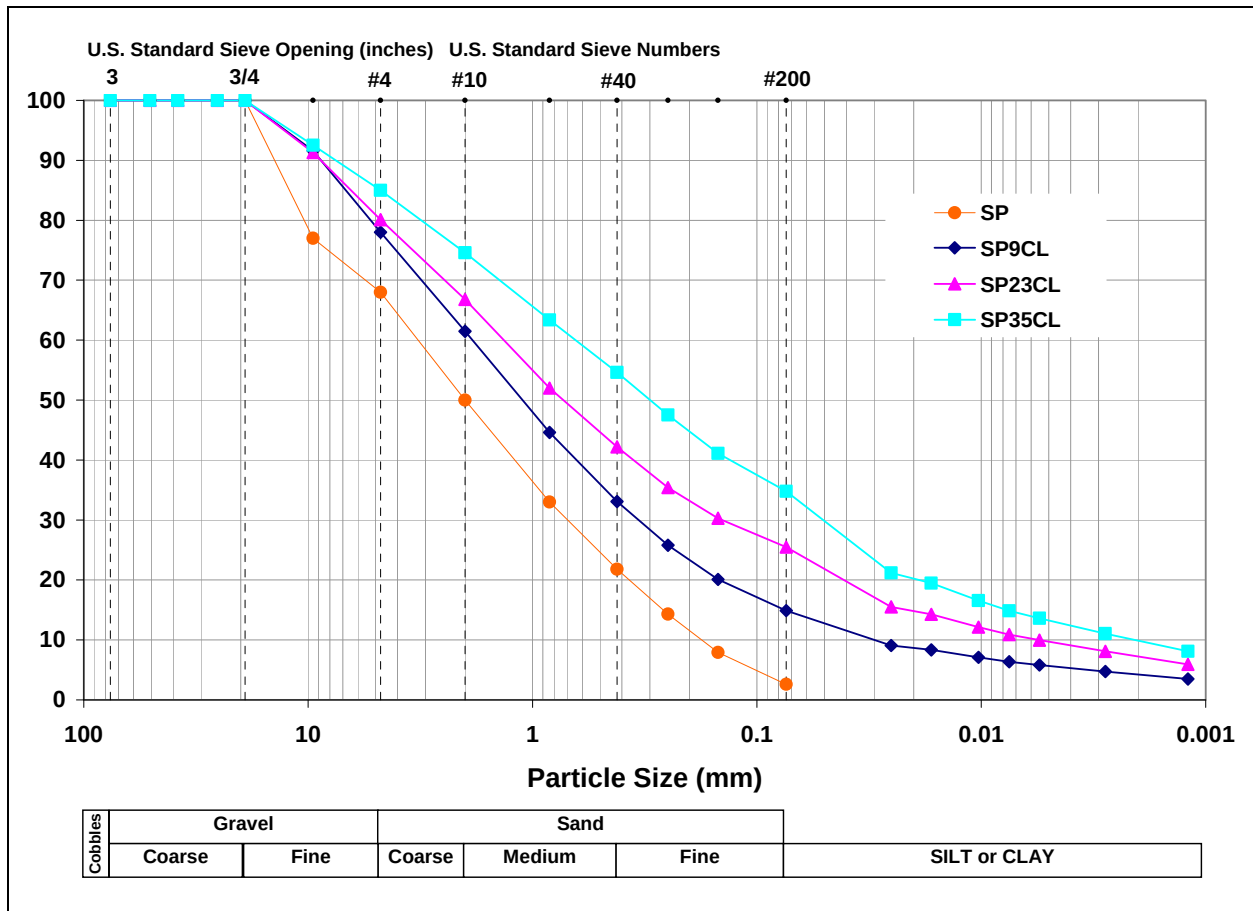


Figure 5. Grain size curves for SP and CL blended soils.

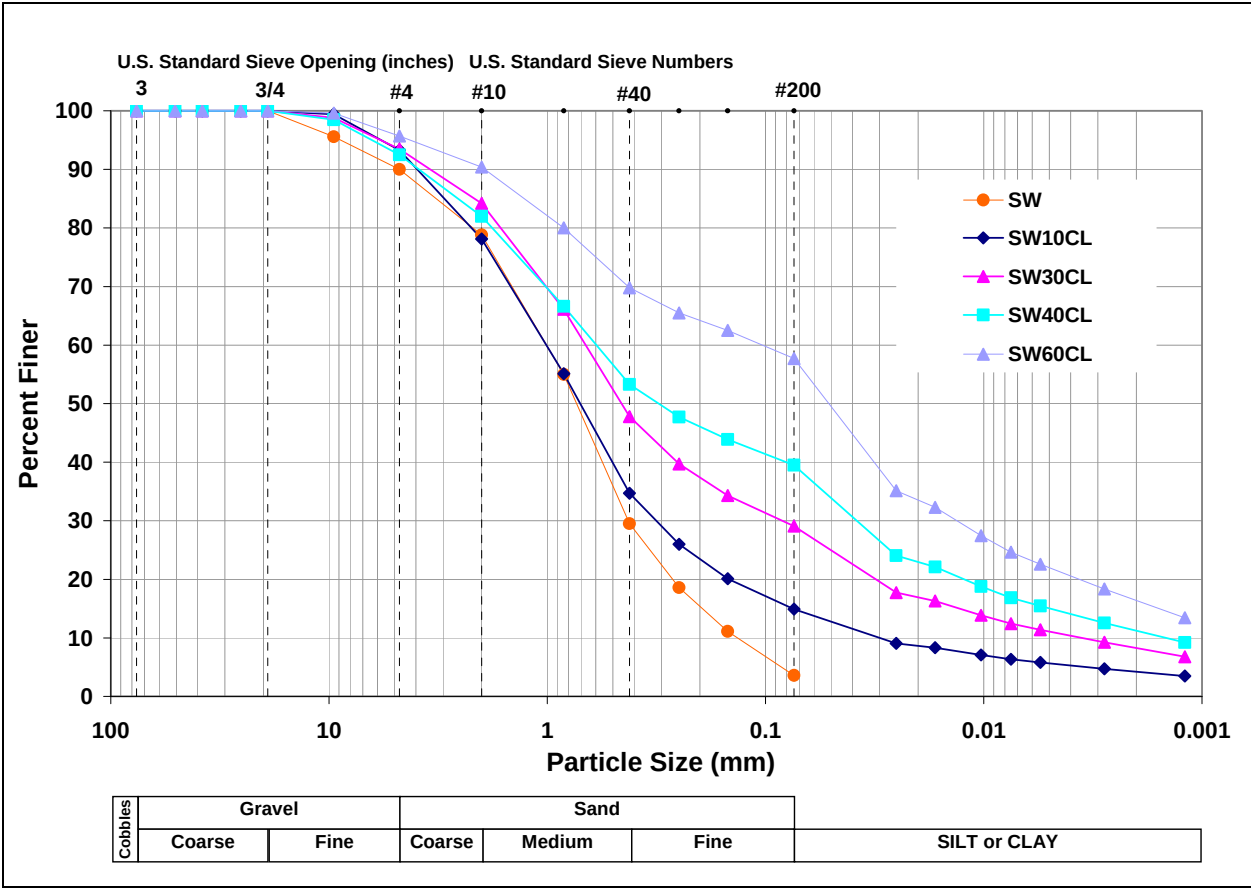


Figure 6. Grain size curves for SW and CL blended soils.

4 Results

4.1 Compactive Effort

4.1.1 Standard and Low-Density Compaction Procedures

Figures 7–11 show the variation in CBR with compactive effort for the five OLS test site soils. These figures include data from samples made with both standard and lower compactive efforts. The samples were tested in the unsoaked soil condition, better representing in-situ field conditions at any time other than immediately after a precipitation event. Moisture/density curves are also provided.

Figure 12 shows the relationship between CBR and moisture content, and density and moisture content for the samples prepared using lower compaction efforts to achieve densities like those found in in-situ soils. Figures 13 and 14 show the soils grouped into non-plastic and plastic categories, to determine whether plasticity may influence soil behavior for these data as some of the CBR inference models indicate (NCHRP 2004). Figures for the individual soils and soil combination samples are presented in Appendix B.

Figure 15 illustrates the relationship of CBR versus density for the low-density samples for all soils. Figures 16 and 17 show the same relationship, with the soils grouped into non-plastic and plastic categories. Figures for the individual soils and soil combination samples are presented in Appendix B.

4.1.2 Poured Samples

CBR results for the poured samples are given in Table 8.

4.2 Soil Moisture Content

4.2.1 Variation of Moisture Content, Soaked and Unsoaked Tests

Figures 18–23 illustrate the change in the relationship between CBR and density for different moisture contents for the five OLS soils and one of the soil combinations.

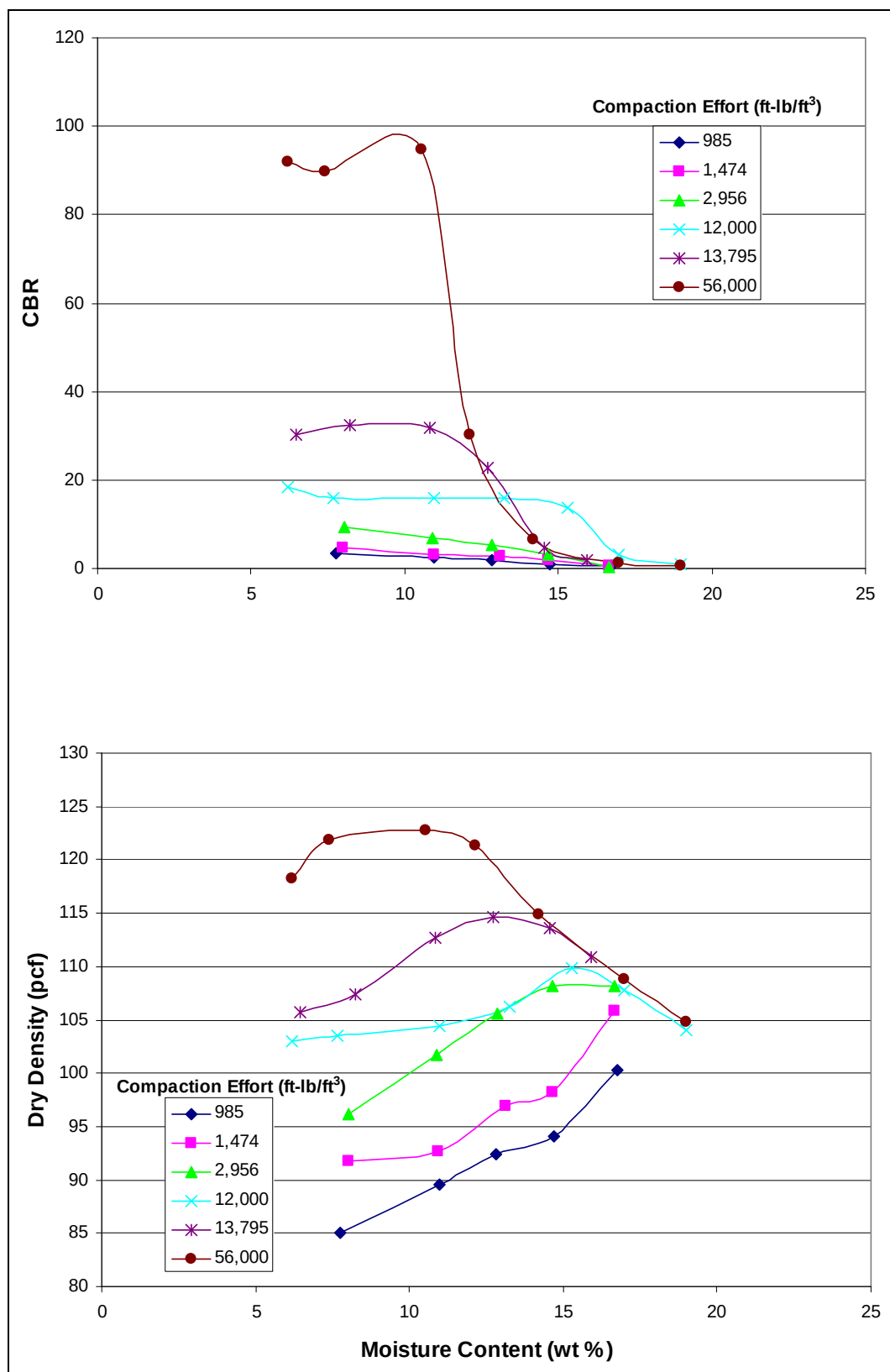


Figure 7. CBR and dry density versus moisture content for Cinci soil.

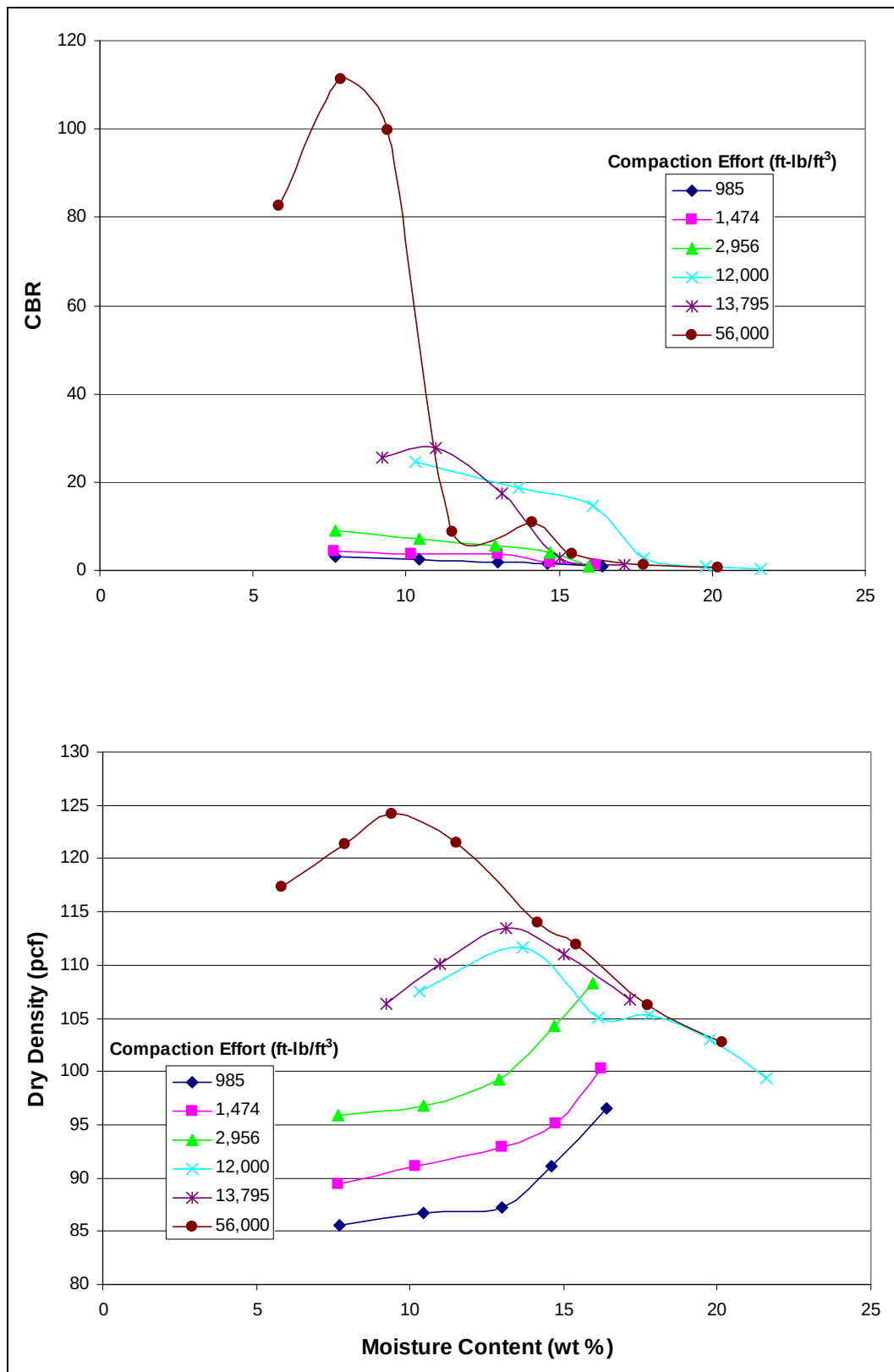


Figure 8. CBR and dry density versus moisture content for Cobb soil.

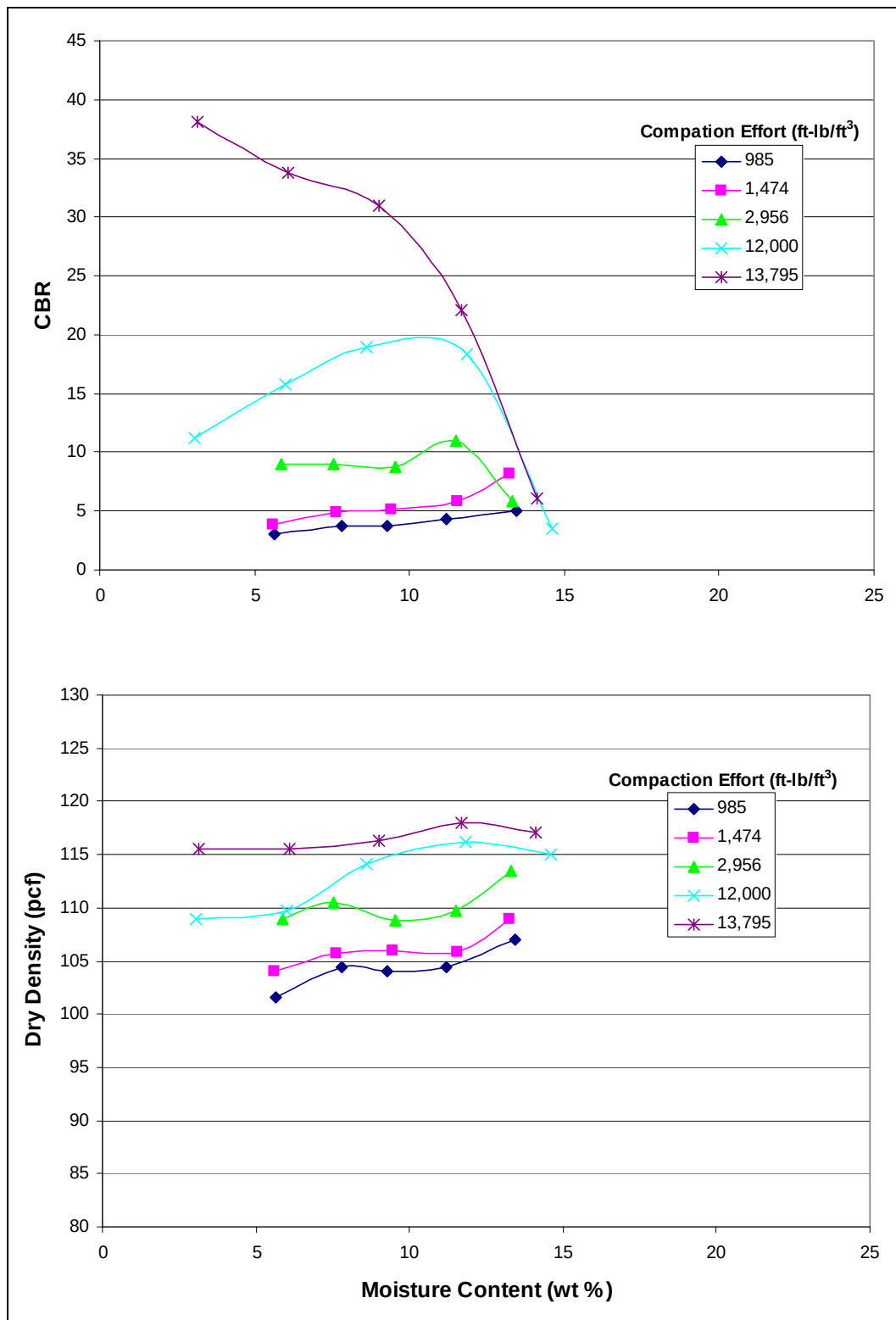


Figure 9. CBR and dry density versus moisture content for El Centro soil.

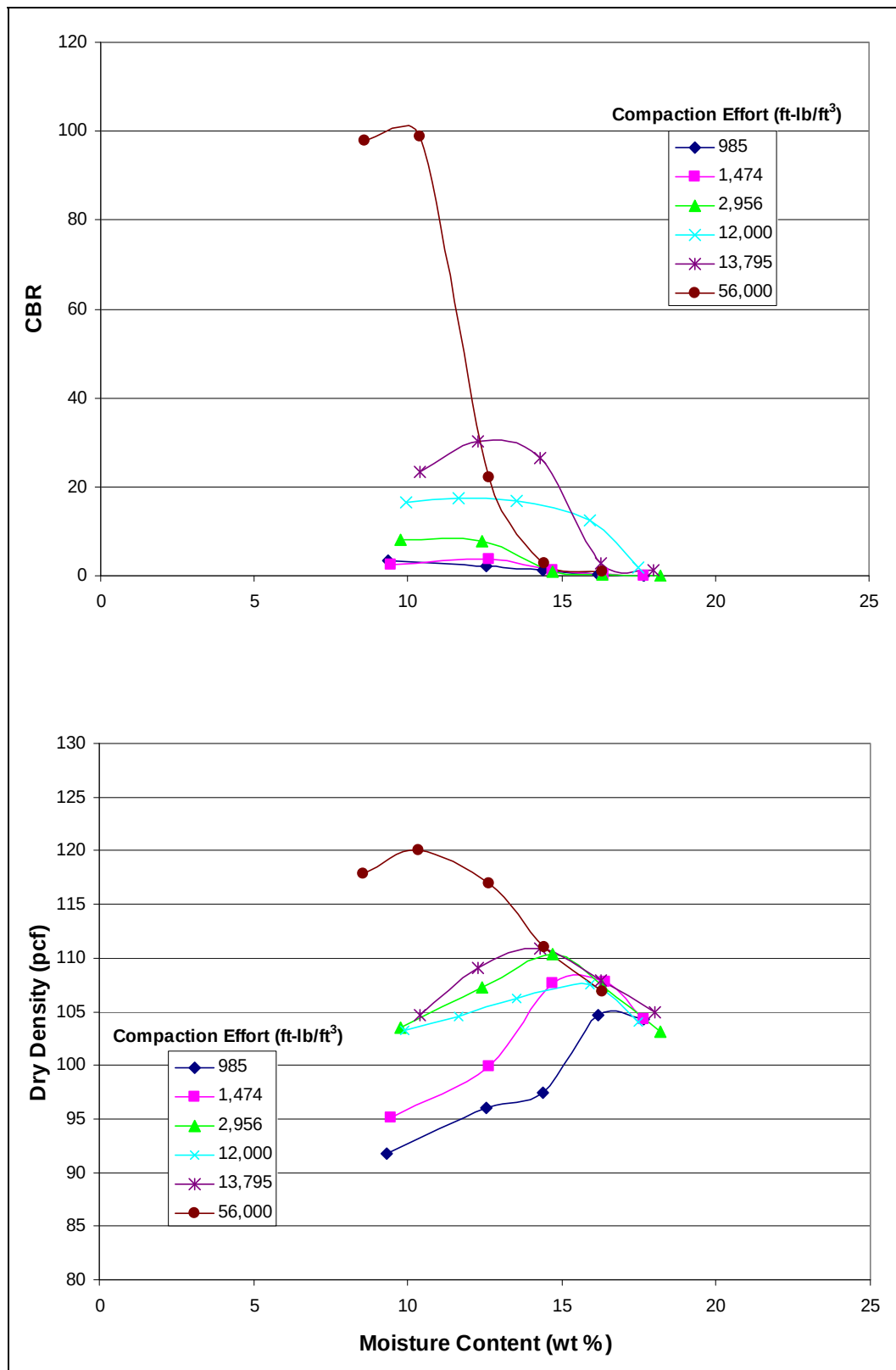


Figure 10. CBR and dry density versus moisture content for Ford Farm soil.

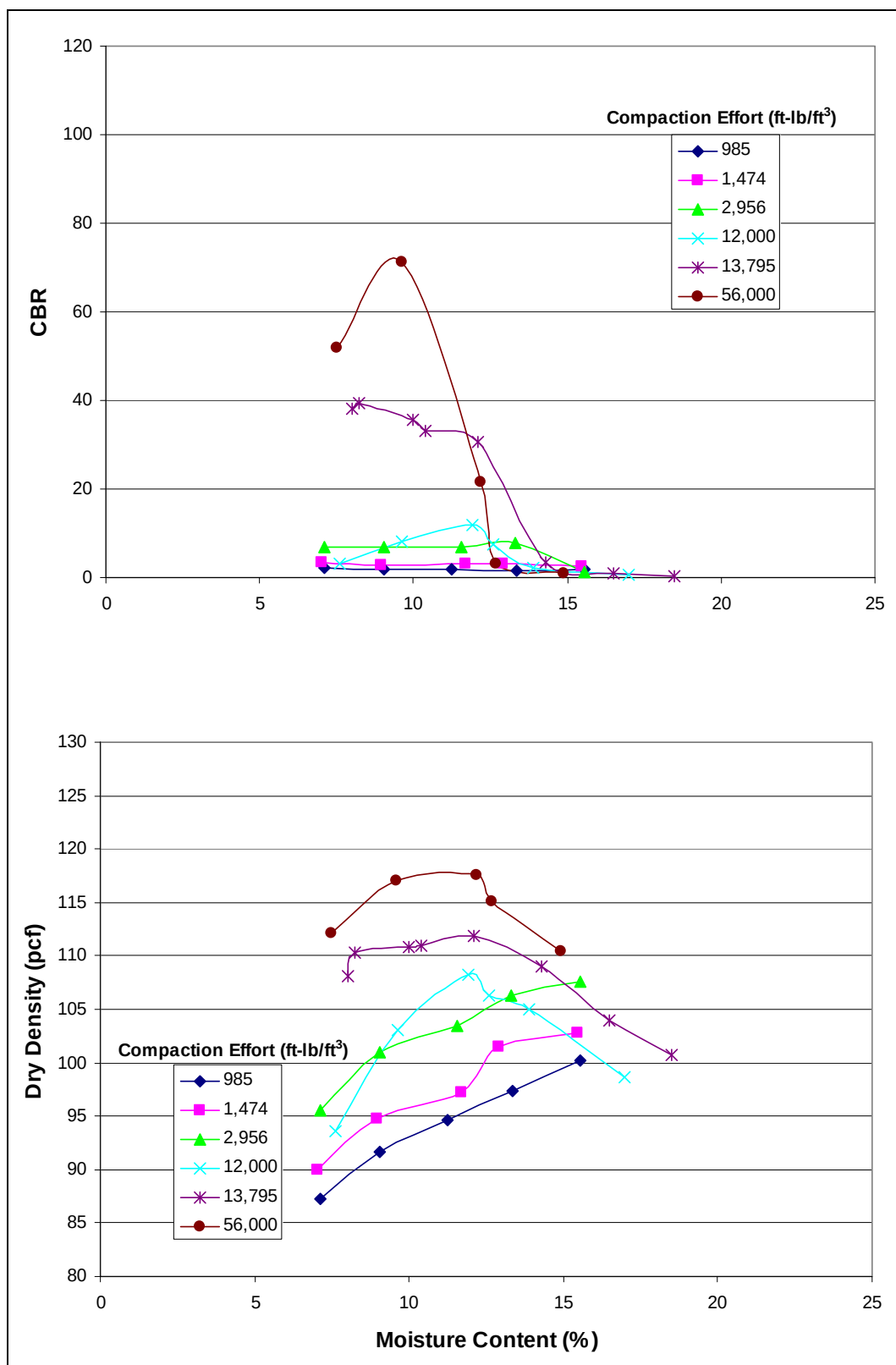


Figure 11. CBR and dry density versus moisture content for Fort Bliss soil.

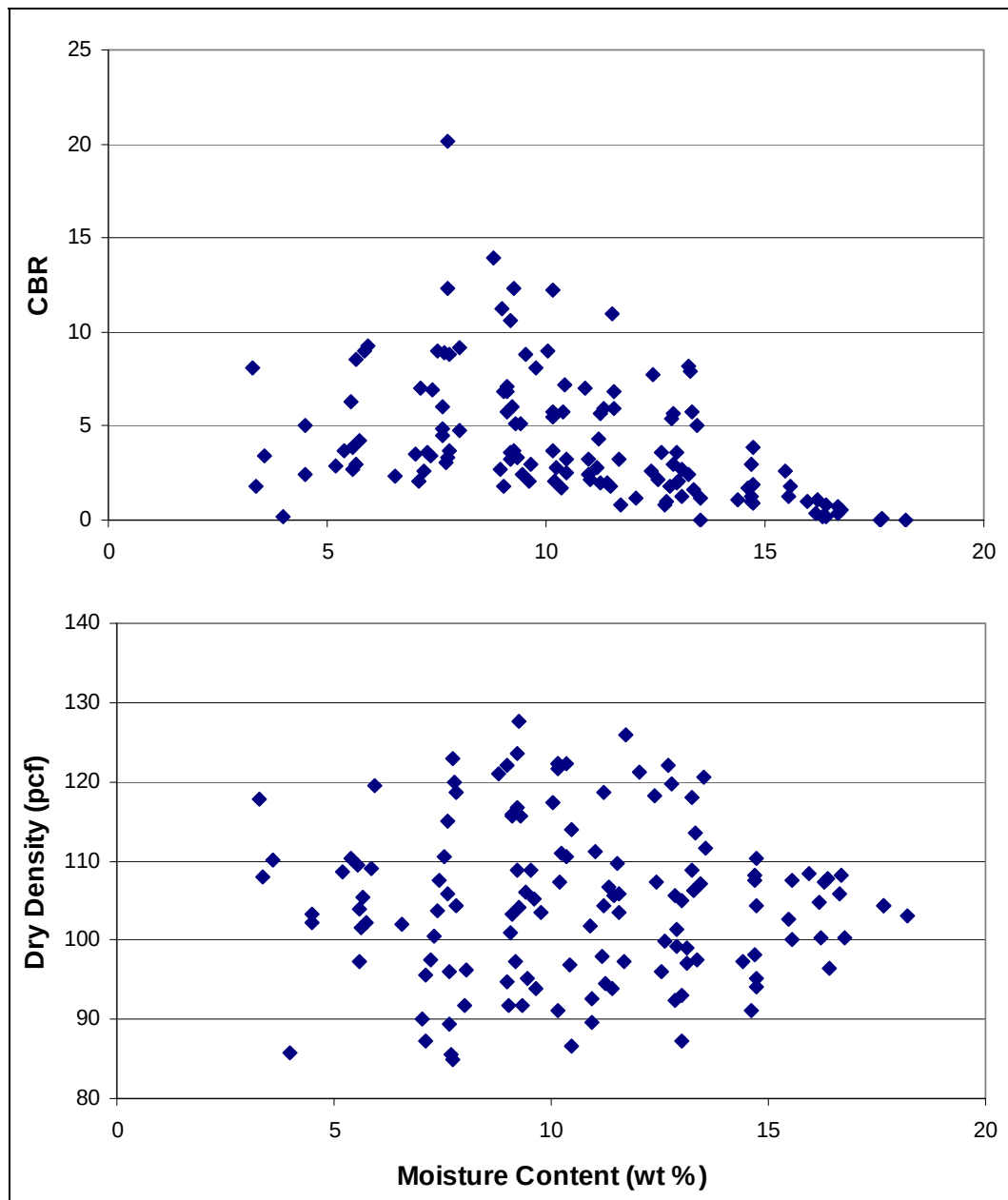


Figure 12. CBR and dry density versus moisture content for low-density samples of all soils.

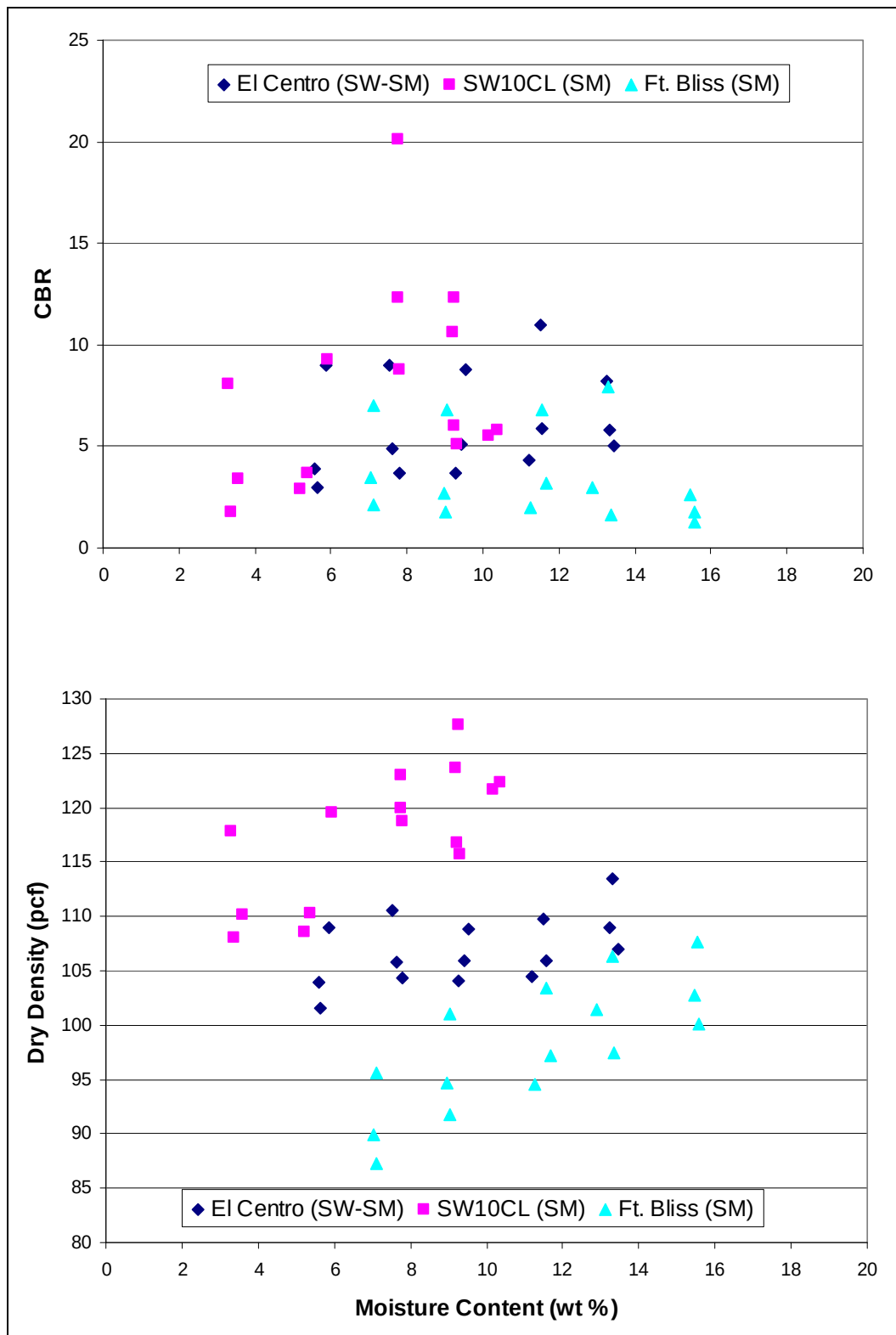


Figure 13. CBR and dry density versus moisture content for low-density samples of non-plastic soils.

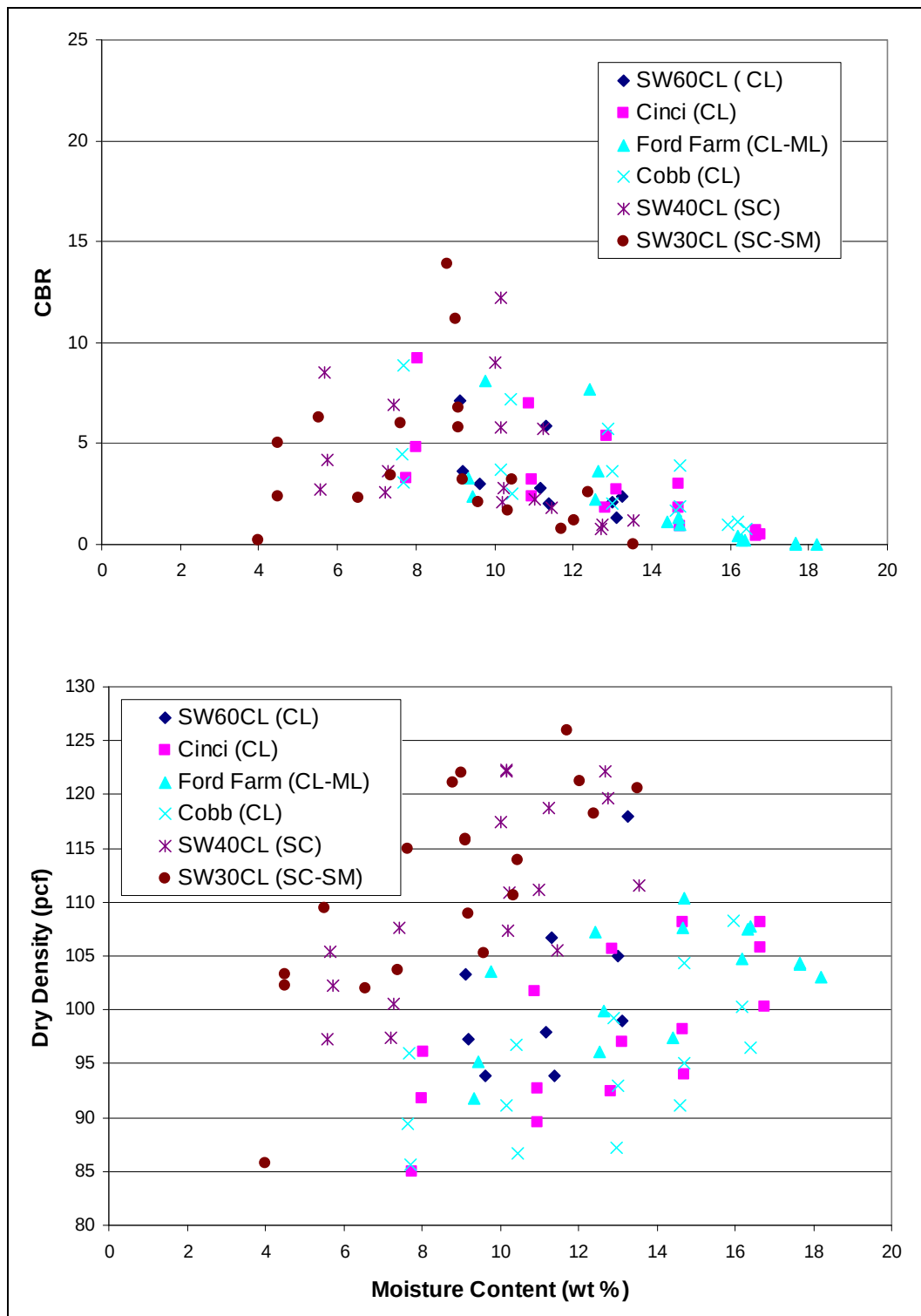


Figure 14. CBR and dry density versus moisture content for low-density samples of plastic soils.

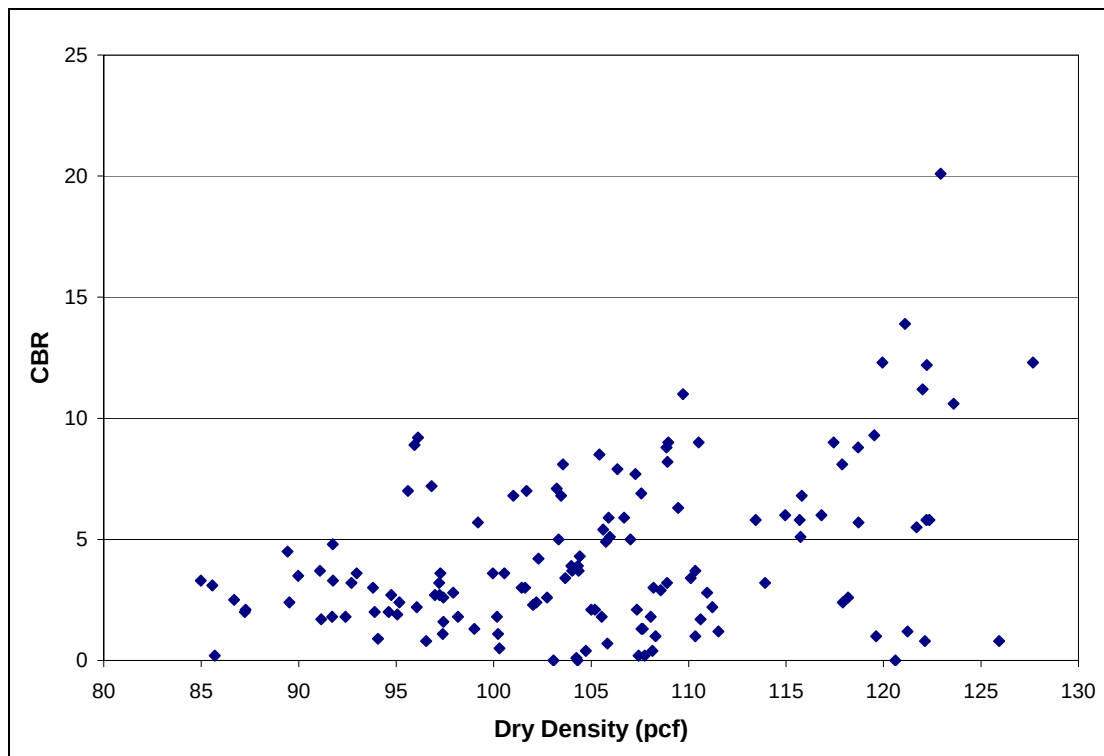


Figure 15. CBR versus density for low-density samples of all soils.

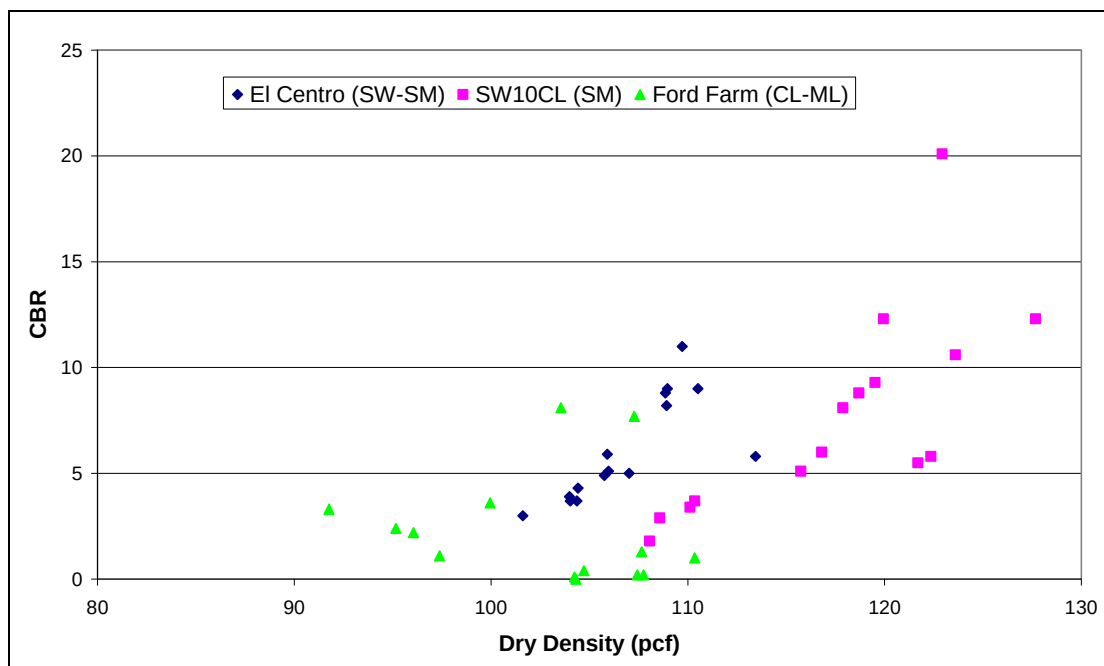


Figure 16. CBR versus density for low-density samples of non-plastic soils.

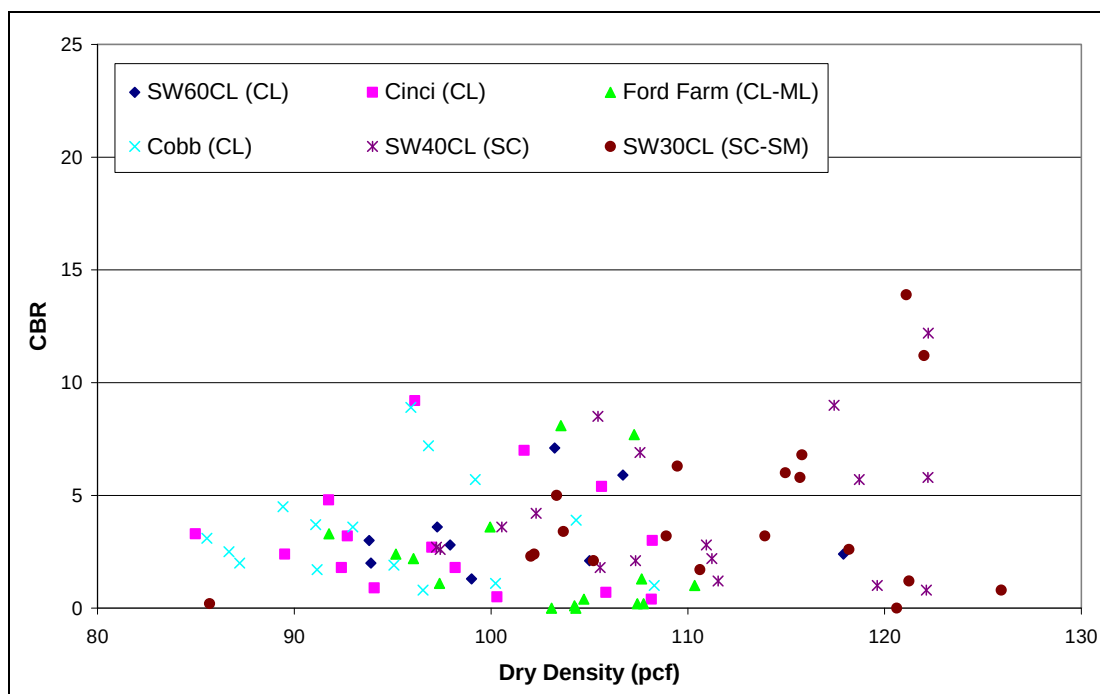


Figure 17. CBR versus density for low-density samples of plastic soils.

The results of the CBR testing on soaked versus unsoaked samples prepared using the standard compaction methods are shown in Figures 24–28.

4.2.2 Wetting and Drying Experiments

Table 8 also gives the CBR and density values for the poured samples that underwent rain, rain/dry, and water table conditioning. Figure 29 shows the variation in the relation between CBR and density for these conditioning treatments.

4.3 Percentage of Fines

Figures 30–33 show the effect of differing amounts of fines on the SW and SP soil combinations. Both CBR and dry density are plotted versus moisture content. The data in these figures are from samples made using the CE-12 compaction effort. Graphs of other compaction efforts are presented in Appendix B.

Table 8. Low-density poured sample CBR values.

Soil name	USCS classification	Poured (No additional treatment)		Rained		Water table		Multiple rain events	
		Density (pcf)	CBR	Density (pcf)	CBR	Density (pcf)	CBR	Density (pcf)	CBR
Cinci	CL	76.9	0.3	87.2	0.7	87.3	0.0	—	—
Cobb	CL	68.1	0.1	75.3	0.2	76.8	0.0	—	—
El Centro	SW-SM	68.3	0.0	90.3	0.2	91.0	0.1	91.0	1.4
Ford Farm	CL-ML	69.4	0.0	91.9	0.3	81.2	0.0	—	—
Fort Bliss	SM	77.7	0.1	81.9	0.3	82.4	0.1	—	—
SP	SP	86.6	0.1	111.5	0.4	114.3	0.3	—	—
SW	SW	83.4	0.0	102.1	0.4	102.3	0.5	—	—
SP5CH	SP-SM	86.3	0.0	105.9	0.2	105.5	0.2	105.4	1.7
SP25CH	SC	82.5	0.3	101.5	0.3	100.4	0.1	101.4	1.2
SP45CH	SC	81.2	0.6	91.6	0.4	91.4	0.2	92.5	1.7
SW5CH	SW-SM	82.4	0.1	96.7	0.2	97.5	0.2	97.4	1.4
SW25CH	SC	80.0	0.2	93.7	0.3	93.3	0.2	92.8	1.2
SW45CH	SC	82.9	0.2	93.6	0.4	94.4	0.1	93.8	2.3
SP9CL	SM	86.2	0.0	109.2	0.2	109.5	0.2	—	—
SP23CL	SC-SM	87.8	0.1	100.9	0.2	100.8	0.1	—	—
SP35CL	SC-SM	90.1	0.2	93.5	0.2	96.6	0.1	93.6	4.5
SW10CL	SM	81.2	0.1	91.8	0.2	90.9	0.2	—	—
SW30CL	SM	85.8	0.2	92.2	0.3	96.7	0.1	—	—
SW40CL	SC	83.4	0.2	91.5	0.2	86.8	0.0	92.7	6.1
SW60CL	CL	81.2	0.3	85.4	0.3	88.0	0.0	—	—

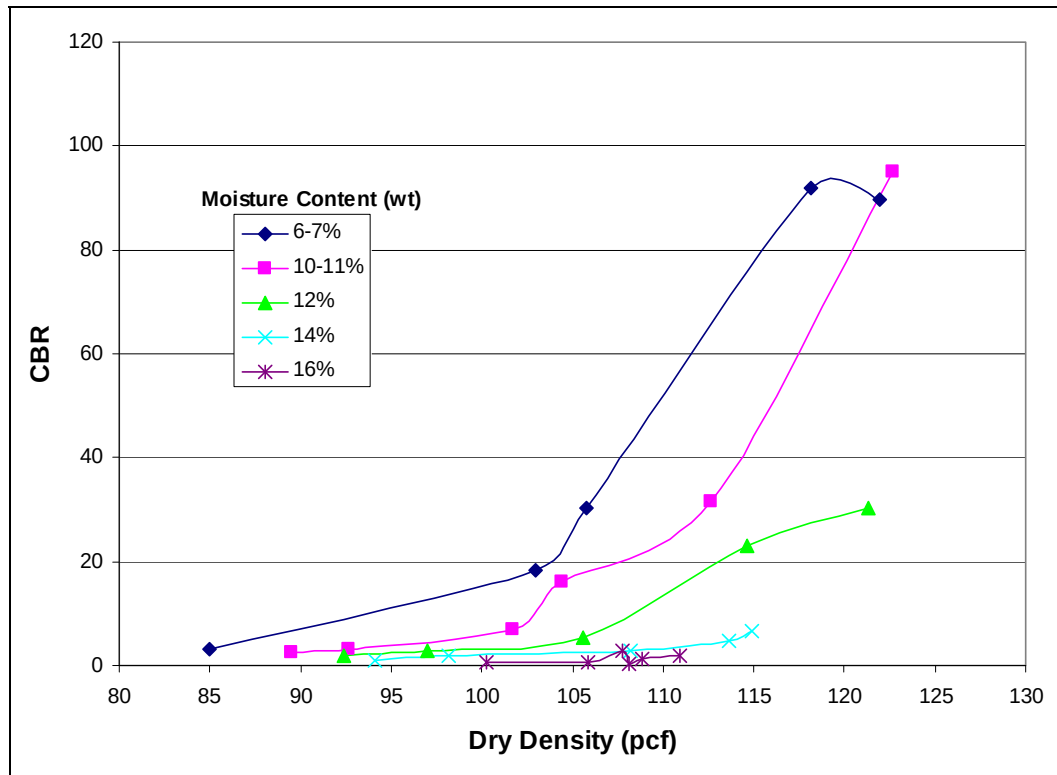


Figure 18. Variation in CBR versus dry density with moisture content for Cinci soil.

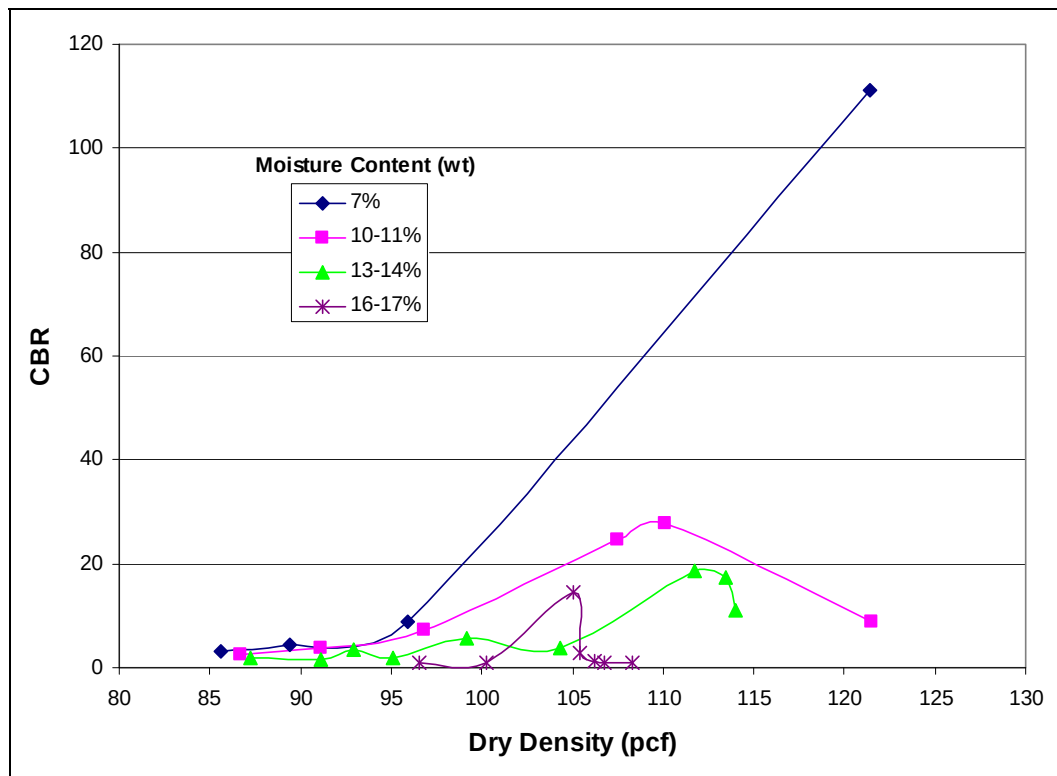


Figure 19. Variation in CBR versus dry density with moisture content for Cobb soil.

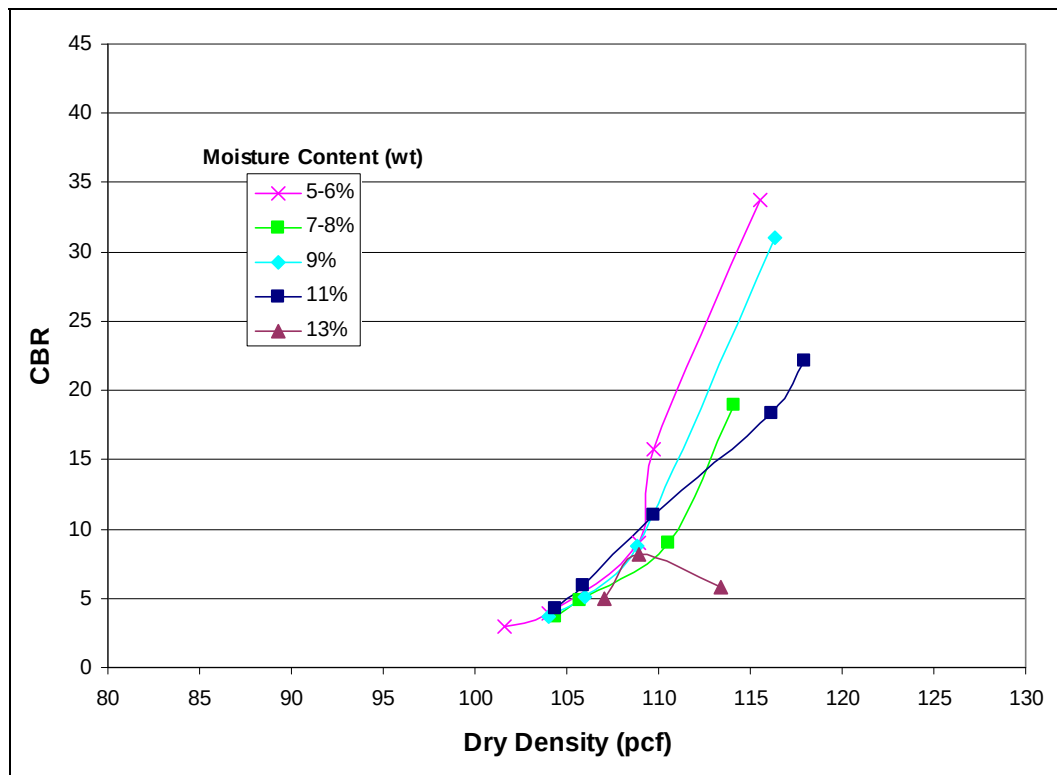


Figure 20. Variation in CBR versus dry density with moisture content for El Centro.

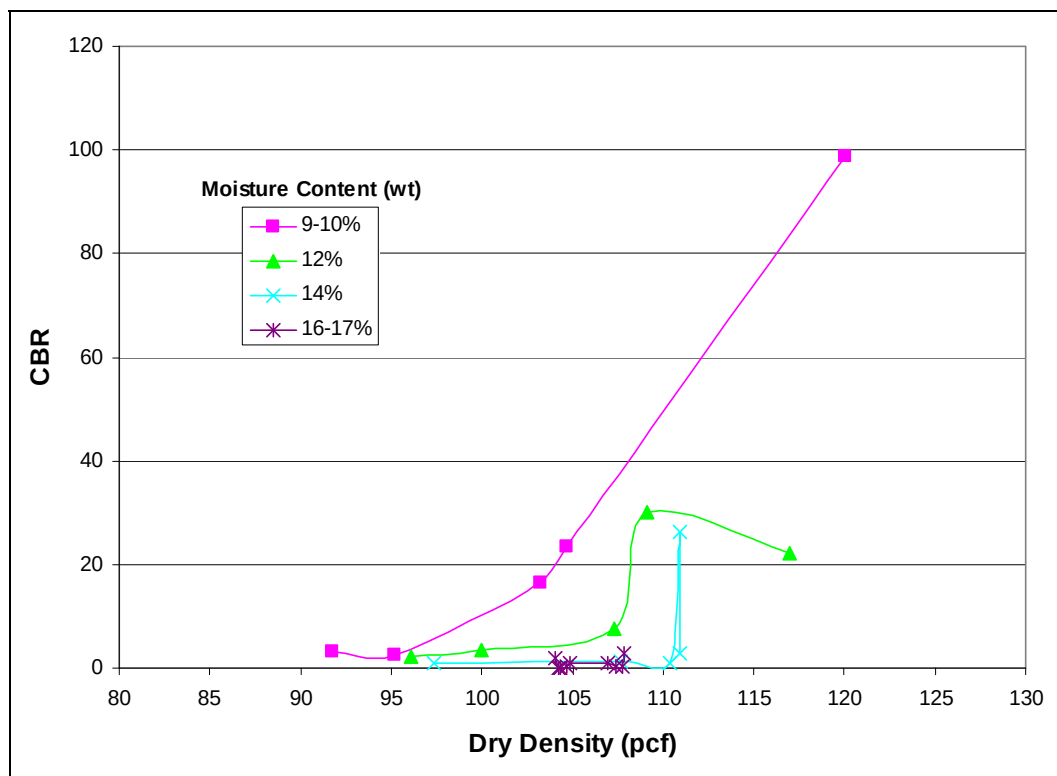


Figure 21. Variation in CBR versus dry density with moisture content for Ford Farm soil.

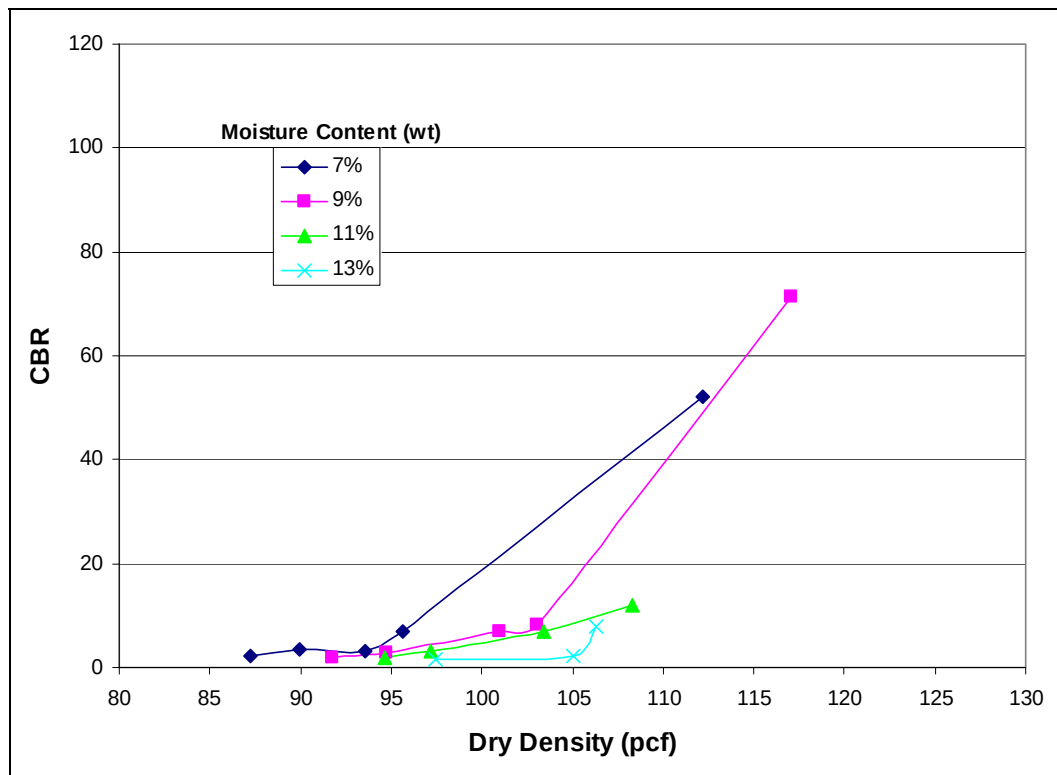


Figure 22. Variation in CBR versus dry density with moisture content for Fort Bliss soil.

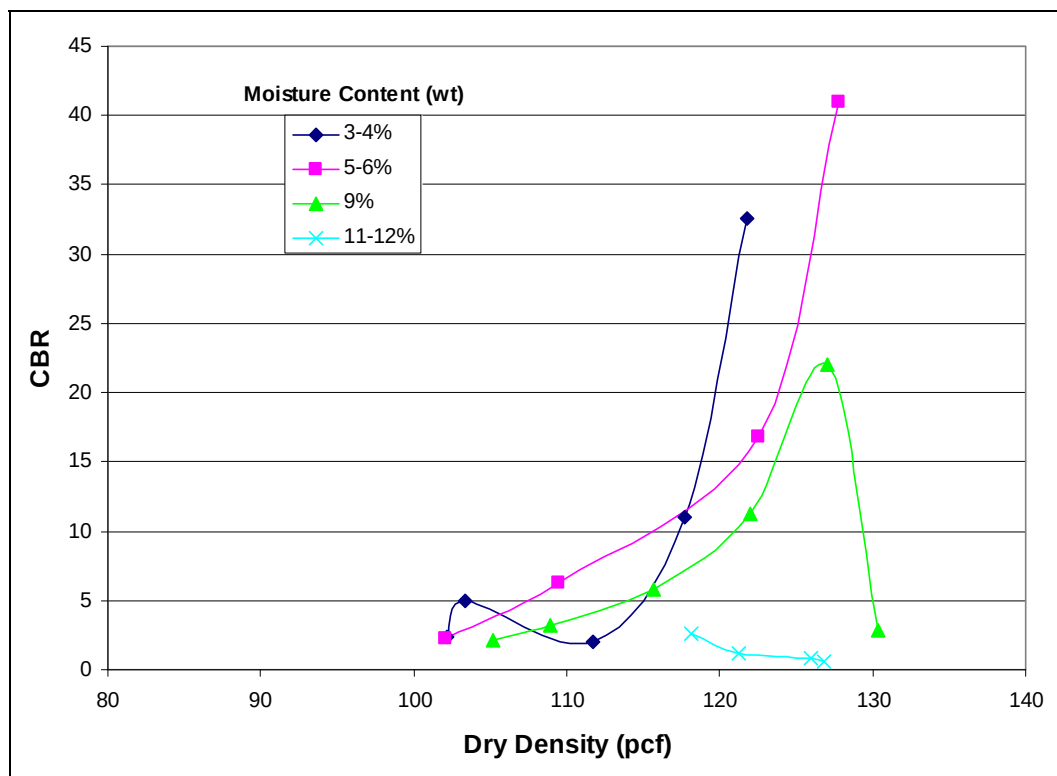


Figure 23. Variation in CBR versus dry density with moisture content for SW30CL soil combination.

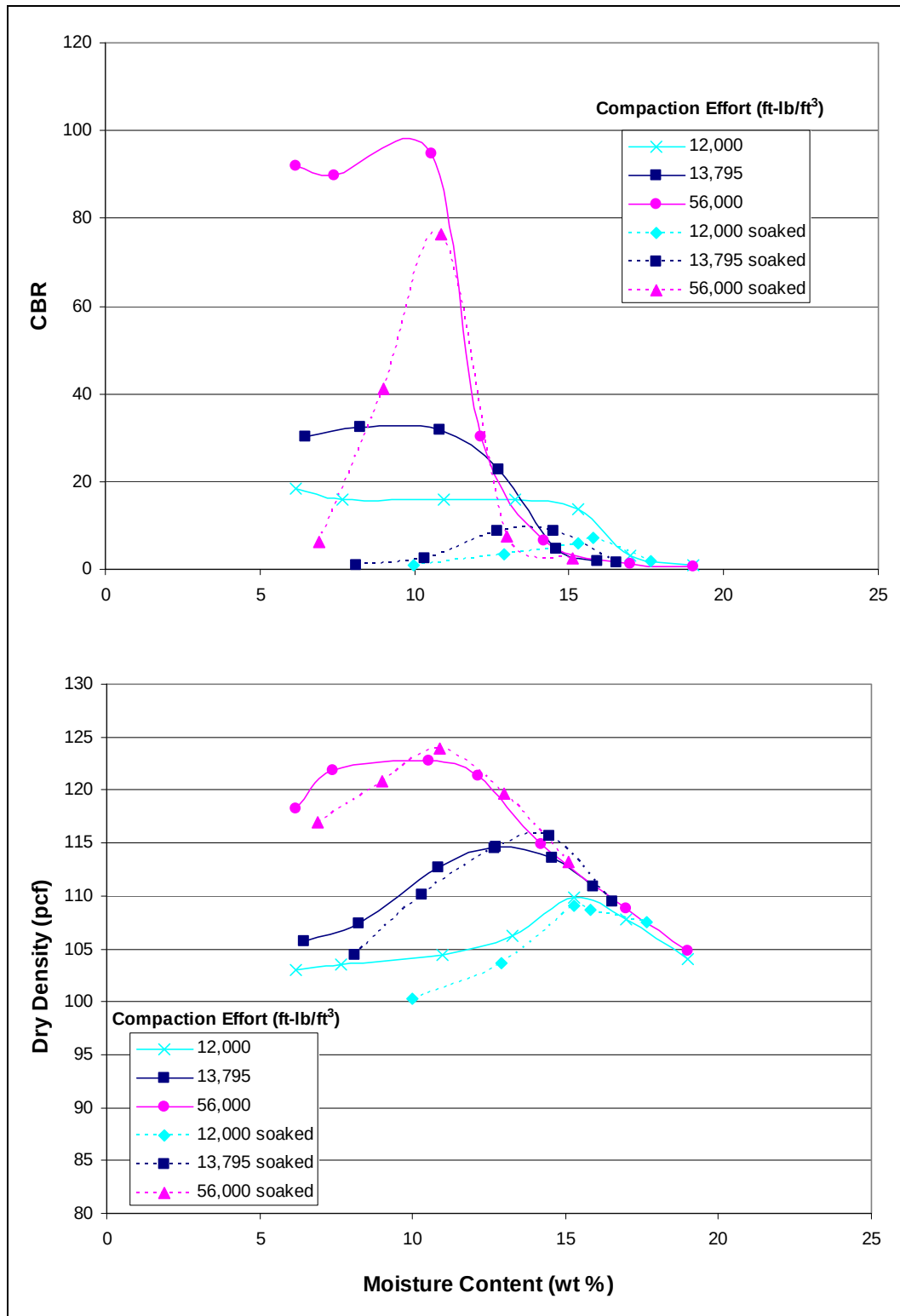


Figure 24. Soaked and unsoaked CBR and dry density versus moisture content for Cinci soil.

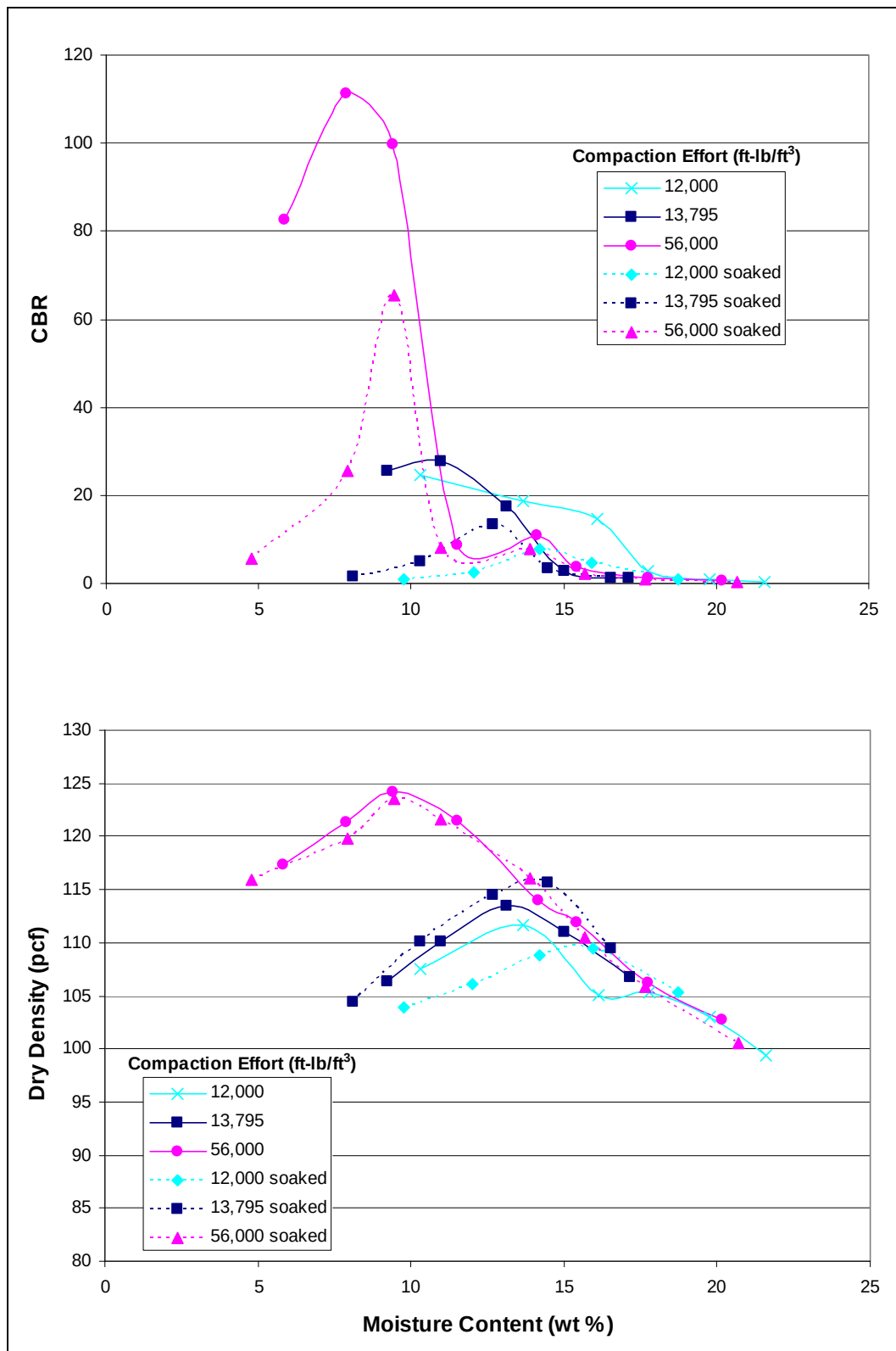


Figure 25. Soaked and unsoaked CBR and dry density versus moisture content for Cobb soil.

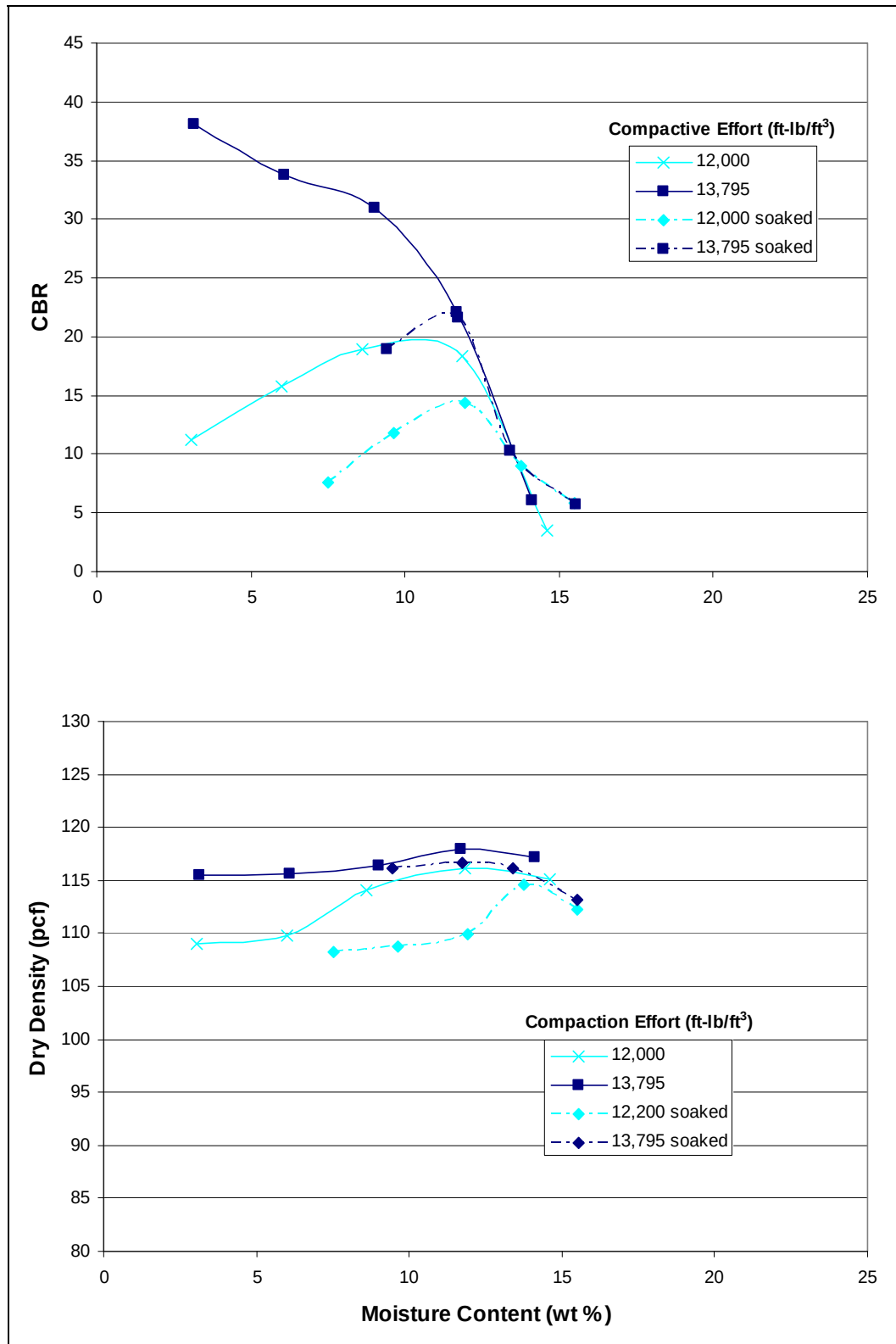


Figure 26. Soaked and unsoaked CBR and dry density versus moisture content for El Centro soil.

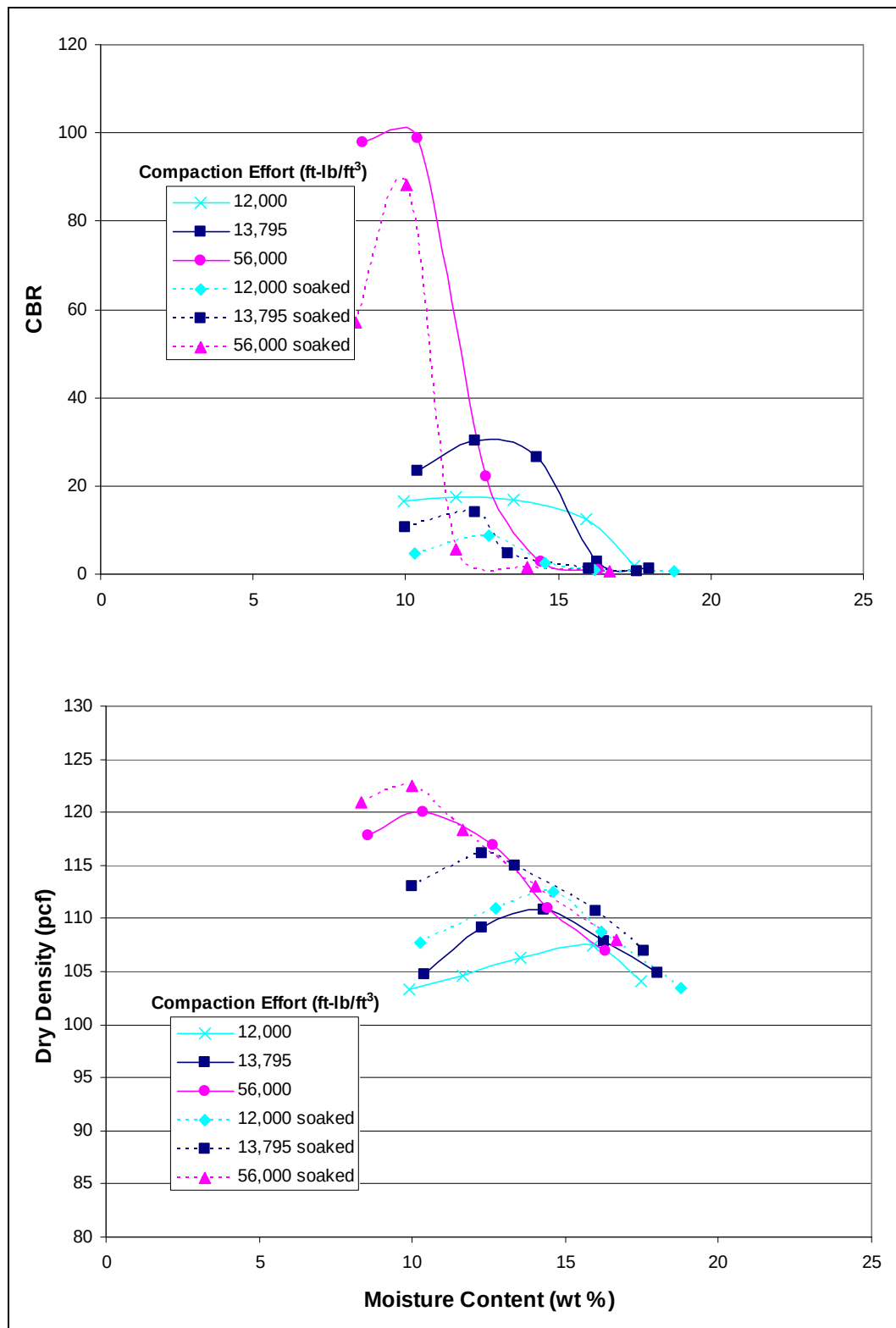


Figure 27. Soaked and unsoaked CBR and dry density versus moisture content for Ford Farm soil.

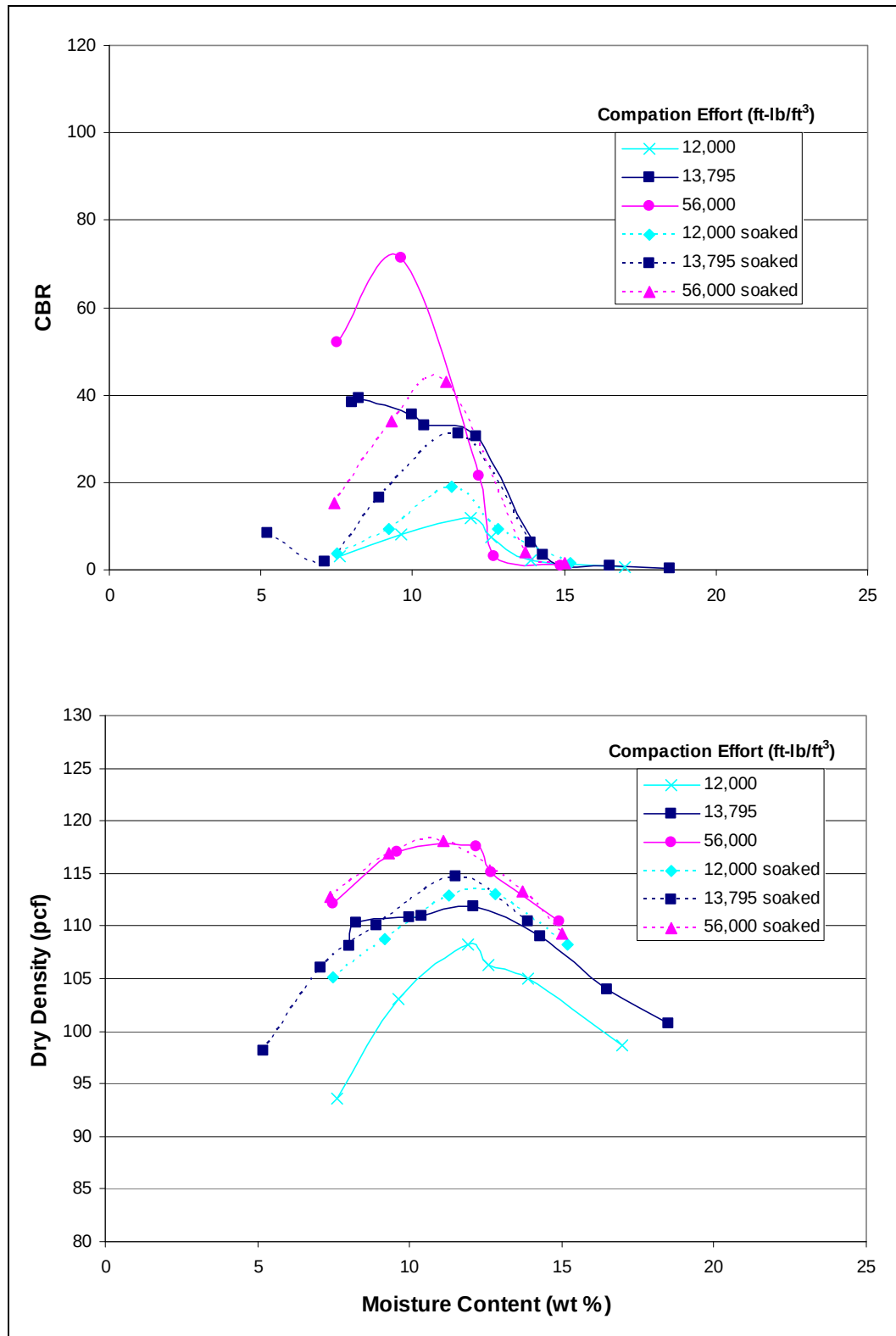


Figure 28. Soaked and unsoaked CBR and dry density versus moisture content for Fort Bliss soil.

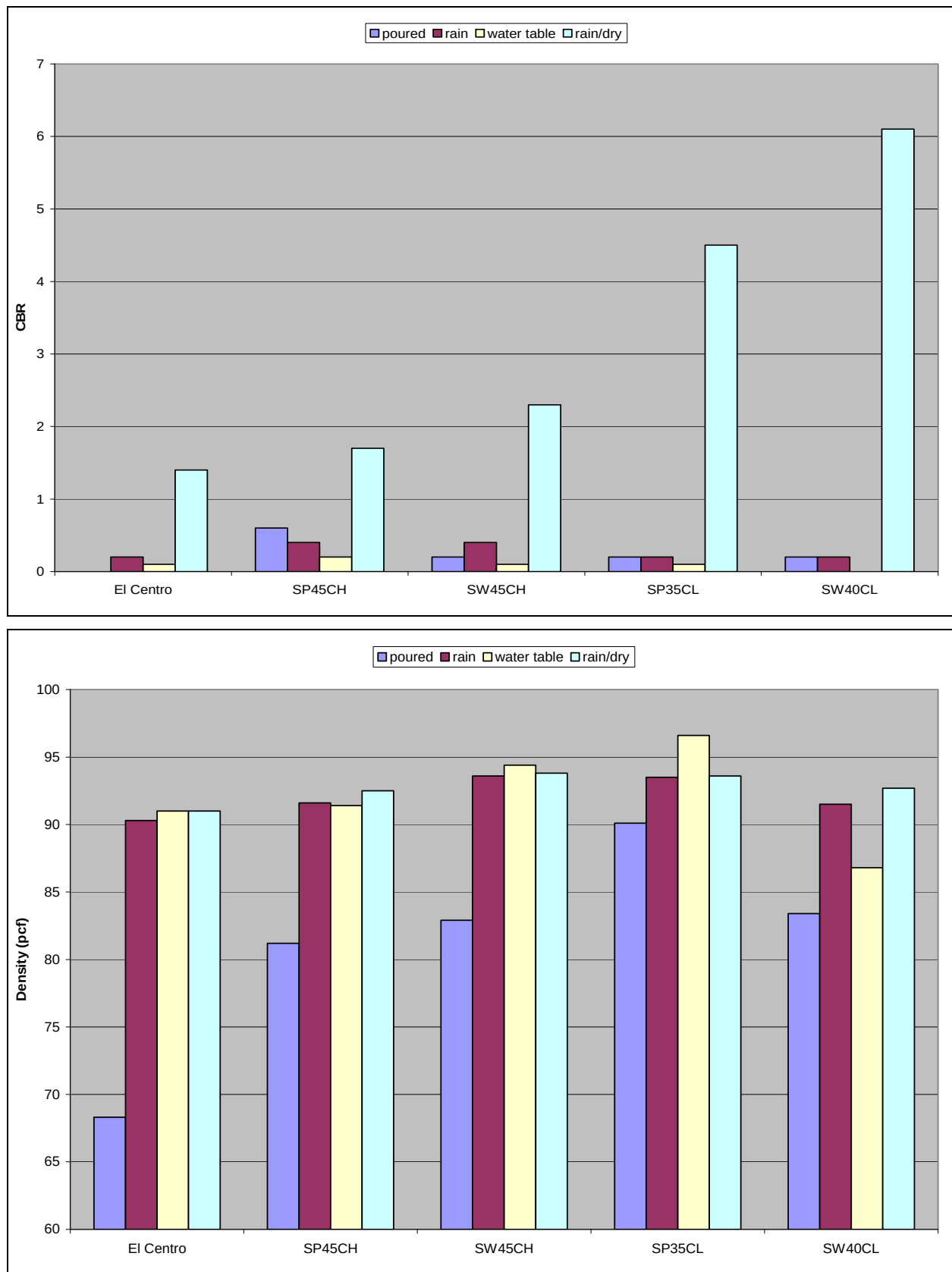


Figure 29. Variation in CBR versus dry density for conditioned poured samples.

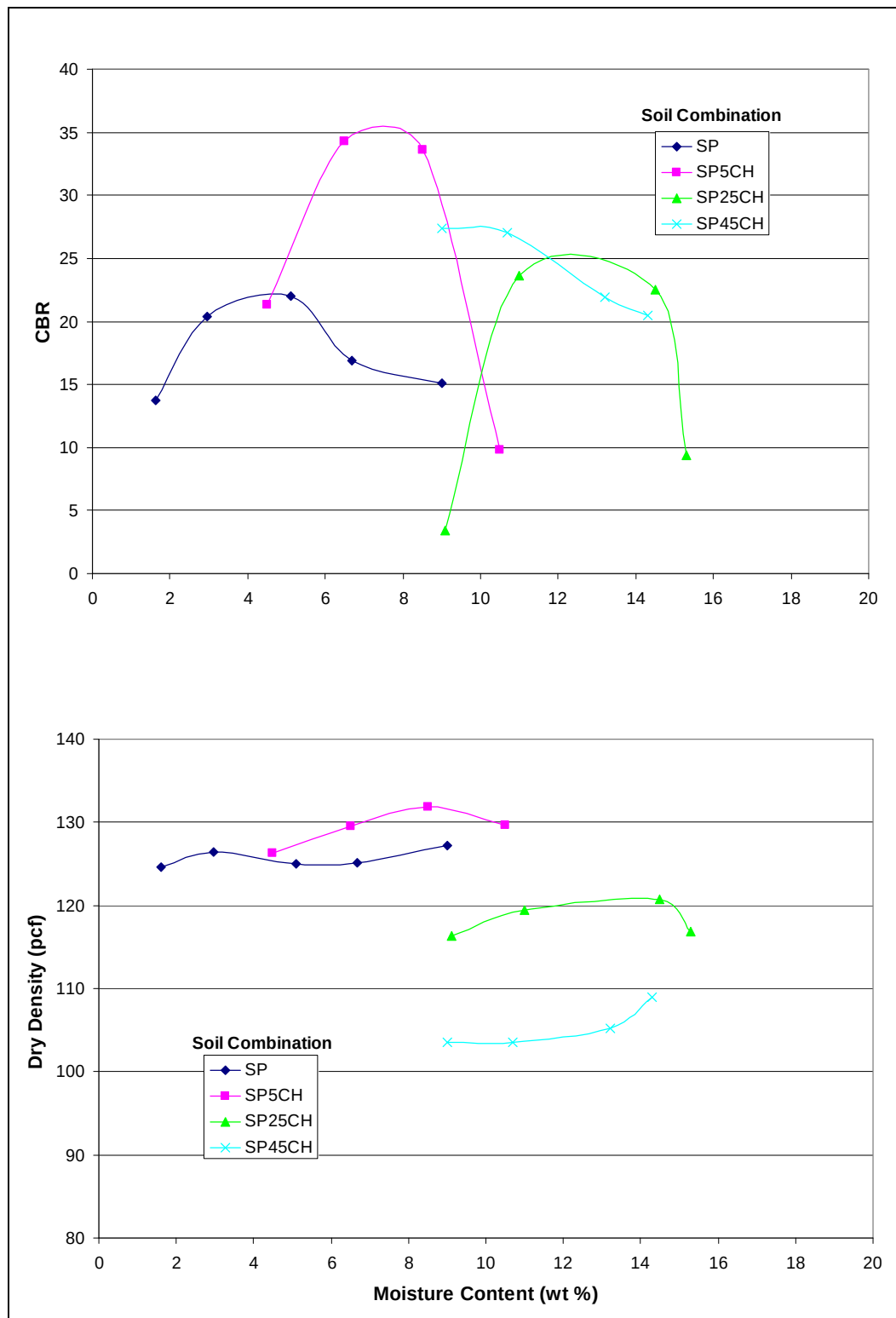


Figure 30. CBR variation with percentage of fines for SP soil combined with CH soil (CE-12 compaction effort).

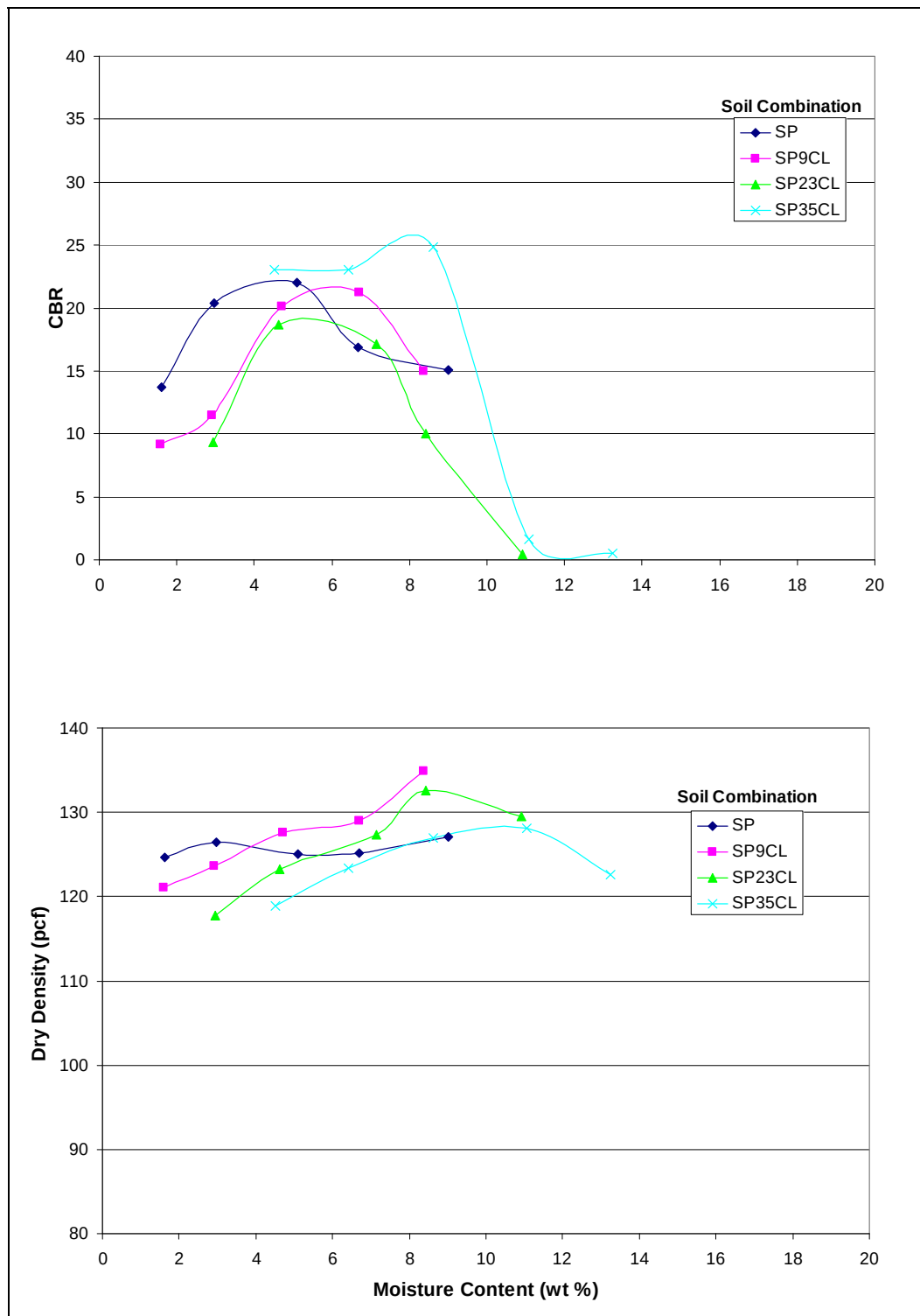


Figure 31. CBR variation with percentage of fines for SP soil combined with CL soil (CE-12 compaction effort).

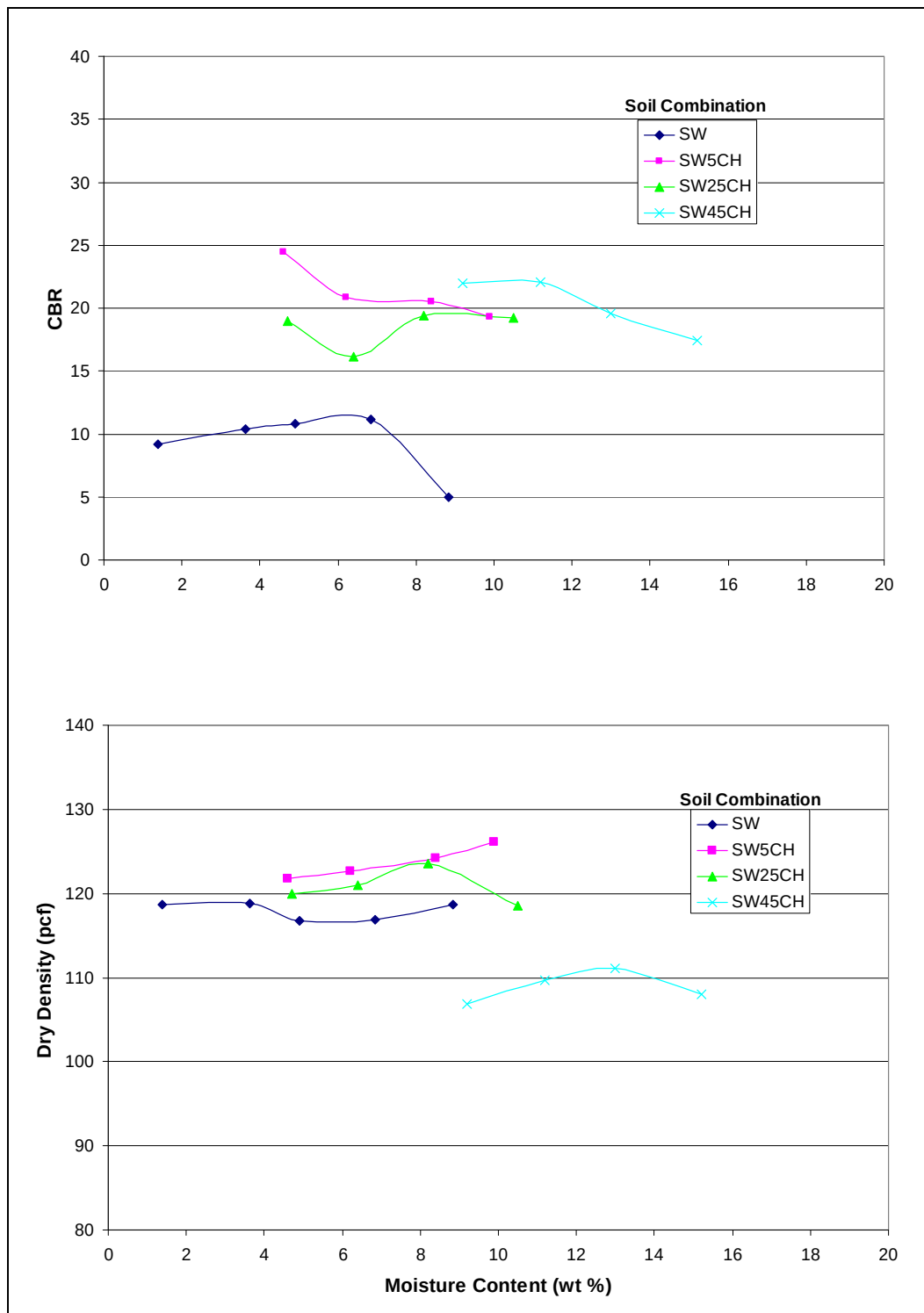


Figure 32. CBR variation with percentage of fines for SW soil combined with CH soil (CE-12 compaction effort).

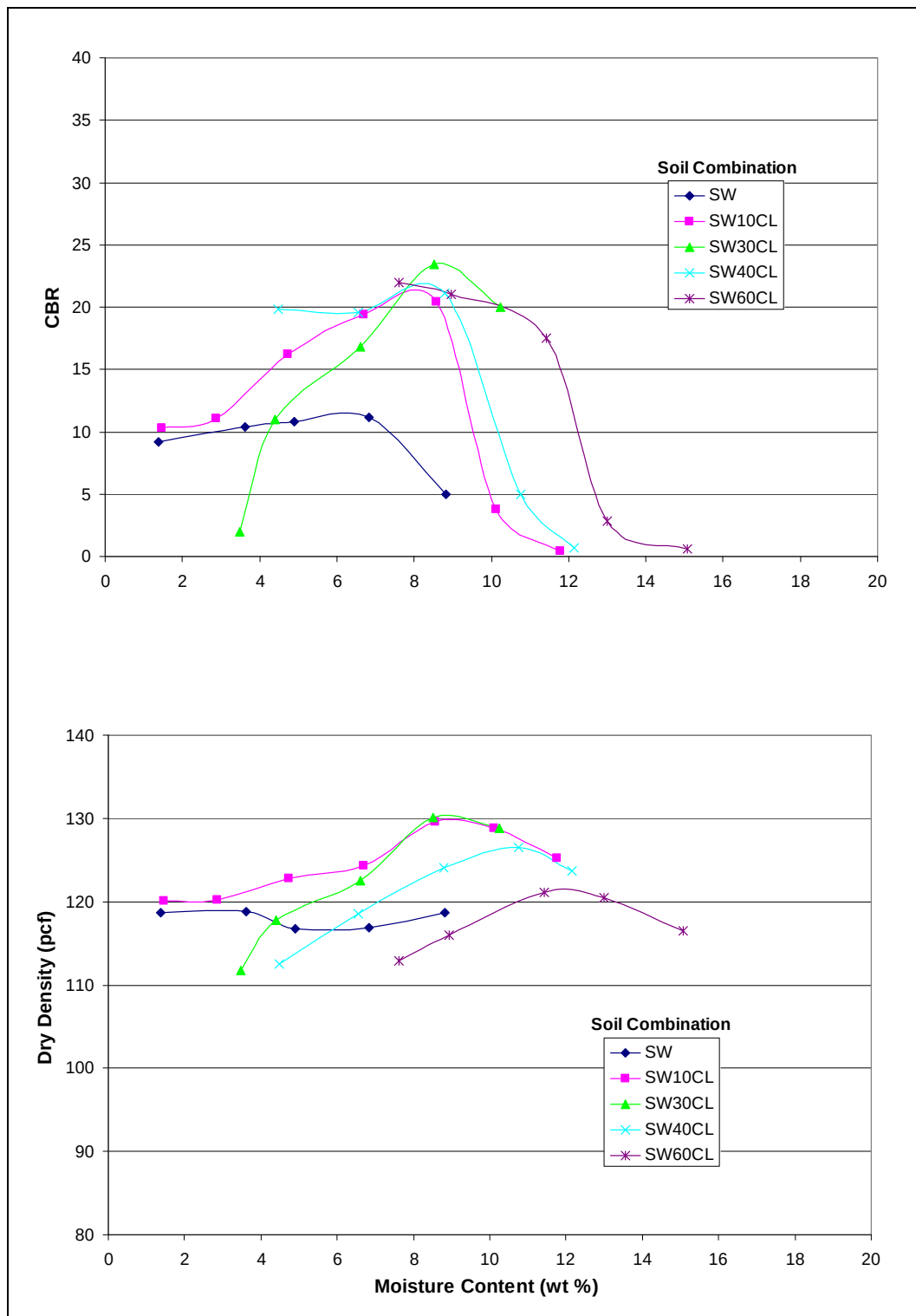


Figure 33. CBR variation with percentage of fines for SW soil combined with CL soil (CE-12 compaction effort).

5 Discussion

5.1 Compactive Effort

5.1.1 Standard and Low-Density Compaction Procedures

Samples prepared from the OLS soils showed increased CBR with increased compaction effort as shown in Figures 7–11. This is as expected, as it is logical that a denser sample of a given soil has a higher bearing capacity. The largest increase in CBR is from the 13,795 to the 56,000 ft-lb/ft³ compaction level. Again, this is to be expected as the other variations between standard compactive efforts are not as large.

It was noted that the optimum moisture contents—the moisture content at which a given soil can be compacted to greatest density—for the samples tend to decrease slightly with increased compaction effort, particularly for the higher compaction efforts. The lower compaction effort soils have flatter, less defined curves than might be expected with low-density soils. When the soil particles are so loosely packed, void ratios and associated moisture contents can vary widely for the same density.

For the low-density samples, Figures 7–11, the change in CBR with increased compaction is not as large, but is still evident. Moisture content seems to have a different effect on CBR with the low-density samples. Two of the soils, Cinci and Cobb, show a slight decrease in CBR with increased moisture content at a given compaction level. For the Ford Farm and Fort Bliss soils, CBR doesn't vary greatly with moisture content, and for the El Centro soil, a slight increase in CBR was seen with increased moisture content. This may have to do with optimum moisture contents for these soils being shifted higher than those seen in soils that were prepared with standard compaction efforts. In Figures 7–9 and 11 it appears that the lower compaction efforts are still dry of optimum; however, the higher moisture contents resulted in decreasing CBR values.

In general, it appears that no matter which compaction effort is used, once the moisture content reaches a range between 12 and 15%, CBR is greatly reduced or nonexistent. The value of the moisture content for this decrease varies with soil type, but in general, this behavior can be seen for all the soils tested.

Figure 15 illustrates the relationship of CBR versus density for the low-density samples for all soils. The samples made with low compactive efforts (i.e., in-situ density) showed CBR values, in general, of less than ten. For densities less than 95 pounds per cubic foot (pcf), CBR values are generally less than five, regardless of soil type or moisture. As densities increase to approximately 120 pcf, CBR values tend to be in the range of zero to ten, the difference being attributable to a combination of soil type and moisture content. As the soil density exceeds 120 pcf, CBR values can increase sharply for small increases in density, but the range of CBR at any given density still can be significant. Again this difference can be attributed to soil type and moisture content, but it seems more pronounced as densities increase.

When further categorized by plasticity, non-plastic soils show more of an effect of density on CBR (Fig. 16) than do plastic soils. For the plastic soils, two of the soils, SW30CL and SW40CL, have a visible increase of CBR with density (Fig. 17), SW30CL more significantly than SW40CL.

Low-density samples also had a very slight tendency for lower CBR with increased moisture content (Fig. 12); density did not seem to significantly change with moisture content, as shown in the bottom of Figure 12. For non-plastic soils, an increase in CBR with moisture content is more evident than for the plastic soils, as is a slight increase in density with moisture content (Fig. 13). For the plastic soils, Cobb and Cinci (both CL soils) have CBR values that decrease very slightly with moisture content, and densities that increase with moisture content (Fig. 14).

For the two soils that have been fully investigated in the field, El Centro and Fort Bliss, the values of CBR obtained during the laboratory program vary somewhat less than those seen in the field. Soil strength measurements taken using a DCP, and converted to CBR, ranged from 1 to 100 at both sites (El Centro dry density 89.9 to 108.9 pcf with moisture contents from 2.2 to 26.6%, Fort Bliss dry density 88.0 to 95.5 pcf with moisture contents from 2.2 to 17.8%) (Affleck et al. in preparation a and b). From the laboratory program, the CBR values for the El Centro soil varied from 0 to 38 (dry density 68.3 to 117.94 pcf with moisture contents from 3.1 to 15.5%). The Fort Bliss CBR values varied from 0.1 to 71 (dry density 77.7 to 118.1 pcf with moisture contents from 3.9 to 18.5%). Therefore, the laboratory effort with sample preparation and testing in a more controlled set-

ting did indeed provide CBR data, over a similar range of densities and moisture contents, with less variability than seen in the field, as desired.

5.1.2 Poured Samples

The CBR values for the poured samples, as shown in Table 8 and Figure 29, are extremely low for any engineering purpose, but include the low end of the CBR range measured in the field at the OLS sites. Generally, CBR values are rounded to the nearest whole number; values shown in Table 8 less than 1.0 are for informational purposes only and it is doubtful these measurements are repeatable. What this does show is that there is no change among treatments. These CBR values would be unable to support aircraft operations in situ. CBR and associated soil properties data for this very low range of CBR are extremely rare because other strength measuring techniques are usually used for quantifying these weak soils (i.e., the vane shear test and cone penetrometers). In current practical application, sites with such low strength would probably be eliminated by visual and “boot-heel” inspection (i.e., walking the site would indicate low bearing capacity) before any soils testing even had been performed.

5.2 Soil Moisture Content

5.2.1 Variation of Moisture Content, Soaked and Unsoaked Tests

Figures 18–23 illustrate the relationship between CBR and density for different moisture contents. For a given soil, it is evident that the CBR may vary considerably for a specific moisture content depending on the density of the soil. Also, these curves illustrate that, given a specific density, the CBR will tend to decrease as moisture content increases.

Figures 24–28 indicate that soaked samples prepared using standard compaction methods, regardless of compactive effort, have much lower CBR values, especially when the samples were prepared drier than optimum moisture content. The decrease in CBR is much less for samples that were prepared with higher moisture contents.

The density of the samples prepared using standard compaction methods was also affected by soaking, but in a varied way. In some cases, soaking a sample prepared at a given compaction effort decreased density (Cinci and El Centro), especially in samples that were prepared at lower moisture contents. In other soils the soaking increased density (Ford Farm and Fort

Bliss), and for the Cobb soil, density of the samples changed very little with soaking.

5.2.2 Wetting and Drying Experiments

Figure 29 shows the variation in the relation between CBR and density for the poured samples that underwent conditioning treatments (i.e., rain, water table, or rain/dry cycle). Poured densities increased for all soils as much as 30% after treatment. Interestingly, in each soil type, the three treatments resulted in relatively similar densities. Although densities increased substantially after treatment, corresponding CBR values remained very low and similar to those of the untreated poured samples except for those subjected to the rain/dry cycling. A dramatic increase in CBR resulted with these samples. Samples with the SW base soil had higher CBR values than samples prepared with the SP base soil, and samples with the CL additive were higher than those with the CH additive. The largest CBR value was for the SW40CL soil combination that underwent the rain/dry conditioning, with a CBR more than six times greater than those resulting from the other treatment methods. This phenomenon may be the result of higher clay contents and/or soil cementation, but it is beyond the scope of this study.

5.3 Percentage of Fines

Figure 30 indicates that for the SP and CH soil combination, additional percentages of CH soil resulted in higher optimum moisture contents and lowered densities as the fine content increased, except for the 5% by weight of CH soil combination, which had an increase in density. The 5% CH mixture had the highest CBR values, but at lower moisture content than the other SP and CH soil combinations. Mixtures with a higher percentage of fines resulted in reduced CBR values, but at higher moisture contents.

The combination of SP with CL soil (Fig. 31) had results similar to the SP and CH combination in that initially low contents (less than 10%) of additives increase density and CBR, followed by a decrease in these values as the fine content is increased. However, the CBR difference is less pronounced using the CH additive than the CL.

For the SW and CH combination, at the higher moisture contents, additional fines produced increased CBR (Fig. 32). This was also true for the

combination of SW with CL soils (Fig. 33). In the lower half of Figure 33, there is also a clear progression of optimum moisture content increasing and density decreasing with additional fines once a threshold of 30% is exceeded.

In Figures 3–6, the curves for SP soils with the CL additive are much smoother than the SP with CH, and both of the SW combinations. The other three distributions tend to gain a hump in the #40 to #200 and finer range. This may explain the different behavior, continual increase of CBR with increase of additive fines, for these three combinations and not for the SP with CL soil combination.

It appears from this limited study that when the fines content is increased relative to a base granular soil, i.e., going from an SP or SM to an SC or CL, there is an initial gain in density and CBR values (up to approximately 10% fines) followed by a decrease in CBR and densities as fines content increases. Generally, as fines content increases, the optimum moisture contents increase, and higher CBR values can be expected.

6 Conclusions

The goal of this study was to produce a controlled, laboratory-generated data set of various soil properties. This laboratory program specifically targeted the effects of fines, compaction energy, density, moisture content, and wetting and drying events on CBR. It is very evident that both the density and moisture content of the soil play a large role in the soil bearing capacity. Generally, soils with higher densities have corresponding lower moisture contents and higher CBR values. The unique data set on low-density soils and low CBR soils is of particular interest to OLS because it helps refine our understanding of engineering properties of low-strength, naturally occurring surface soils, and provides data for the database in a range of values previously lacking. The wetting and drying experiments also contribute new knowledge on the impact of moisture content on soil strength.

It is more important to the OLS program that this laboratory program has provided additional CBR data, over a controlled range of densities and moisture contents, for use in the OLS software that models soil strength as part of the site selection process. It also initially appears to have provided data with less variability than seen in two OLS field site evaluations where CBR was correlated from field DCP measurements.

7 References

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Appendix A: Soil Grain Size Curves

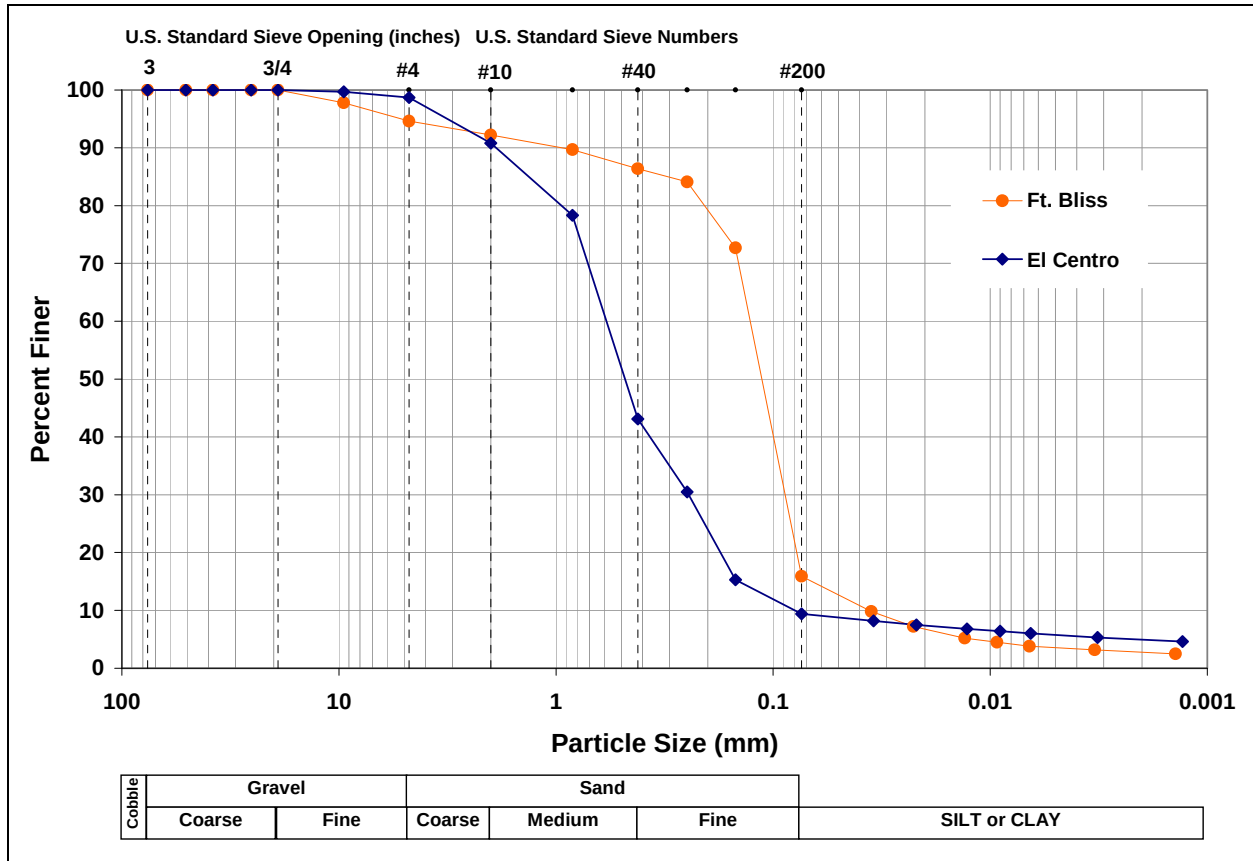


Figure A-1. Grain size curves for El Centro and Fort Bliss soils.

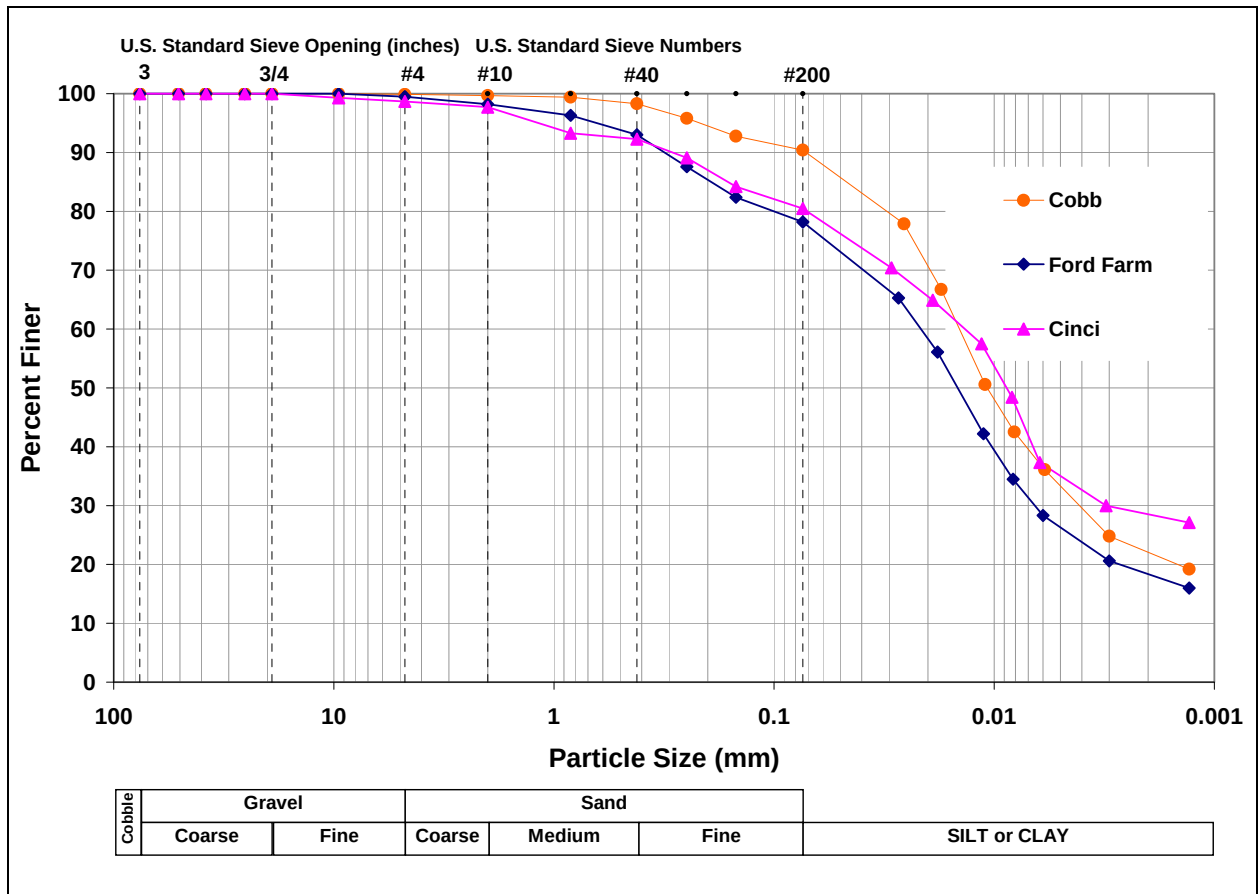


Figure A-2. Grain size curves for Indiana soils (Cobb, Ford Farm, and Cinci).

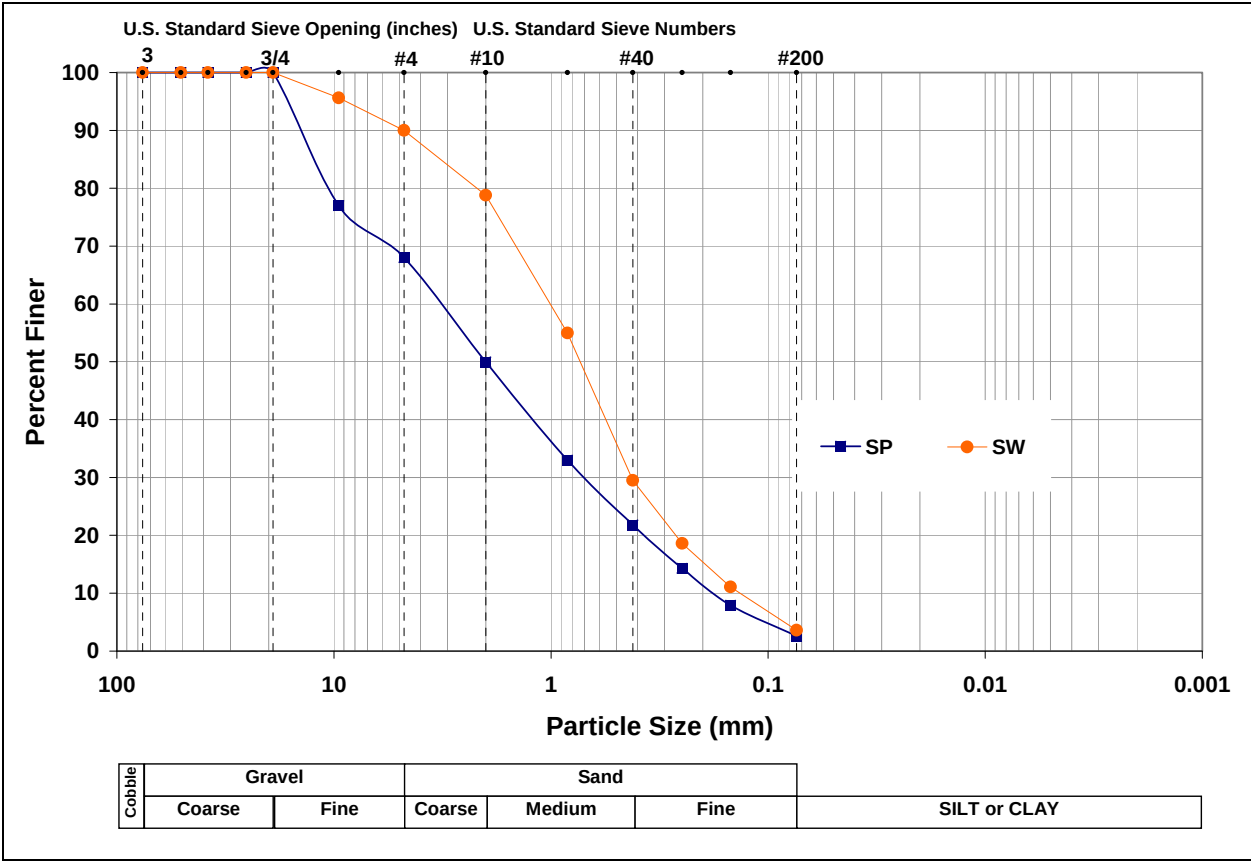


Figure A-3. Grain size curves for SP and SW base soils.

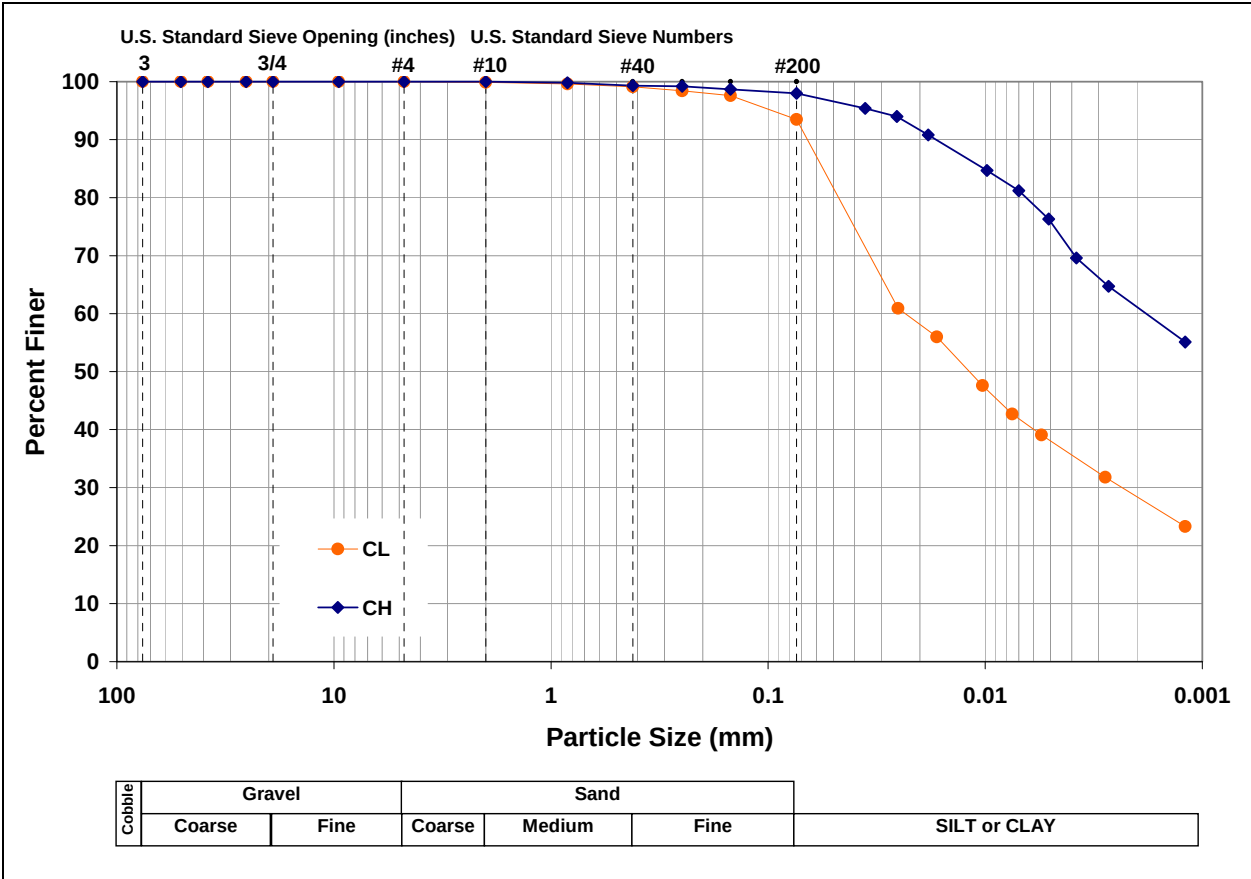


Figure A-4. Grain size curves for CL and CH additive soils.

Appendix B: Additional Plots and Graphics

B1 CBR and Dry Density Versus Moisture Content, Low-Density Samples

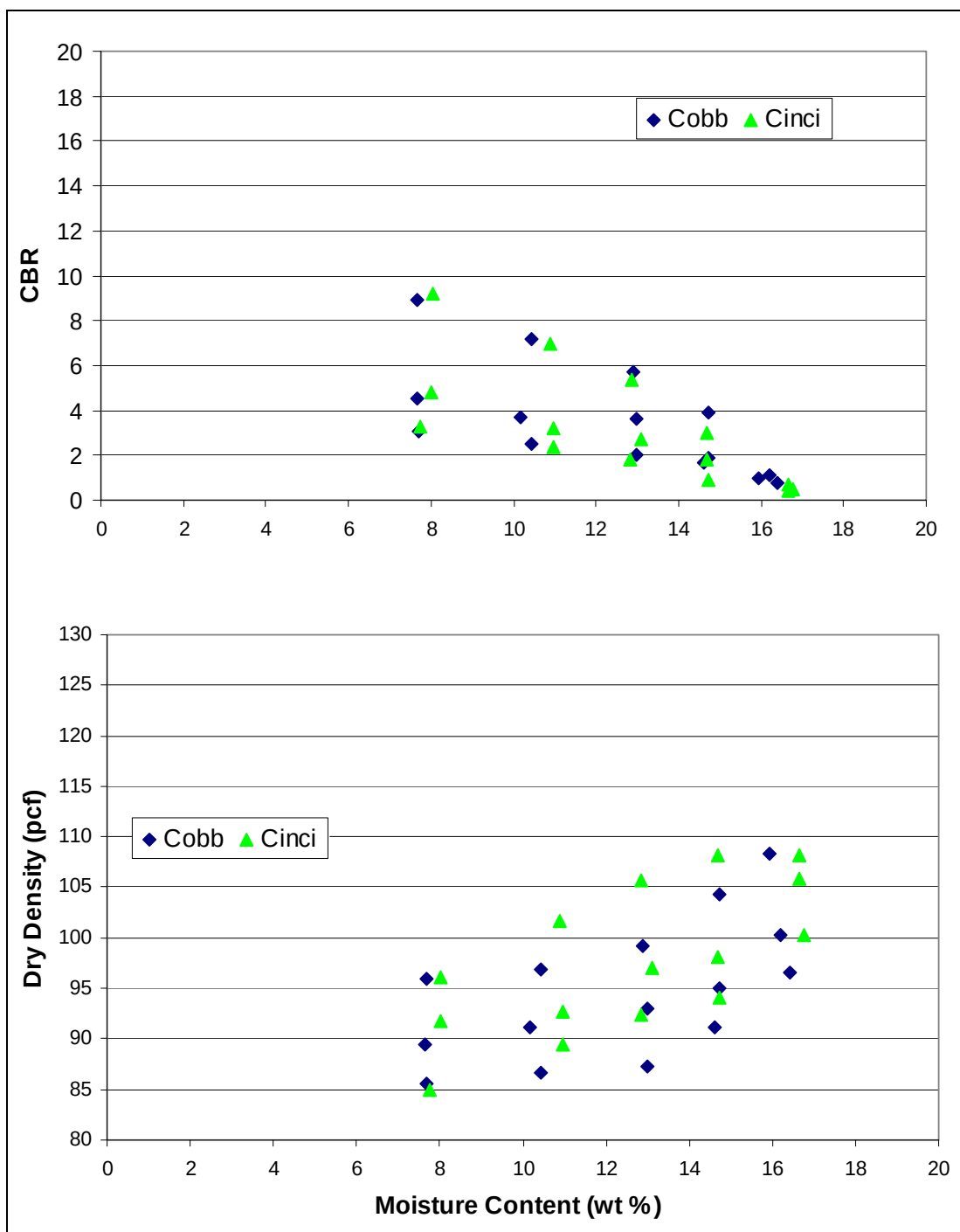


Figure B-1. CBR and dry density versus moisture content for low-density samples of CL soils.

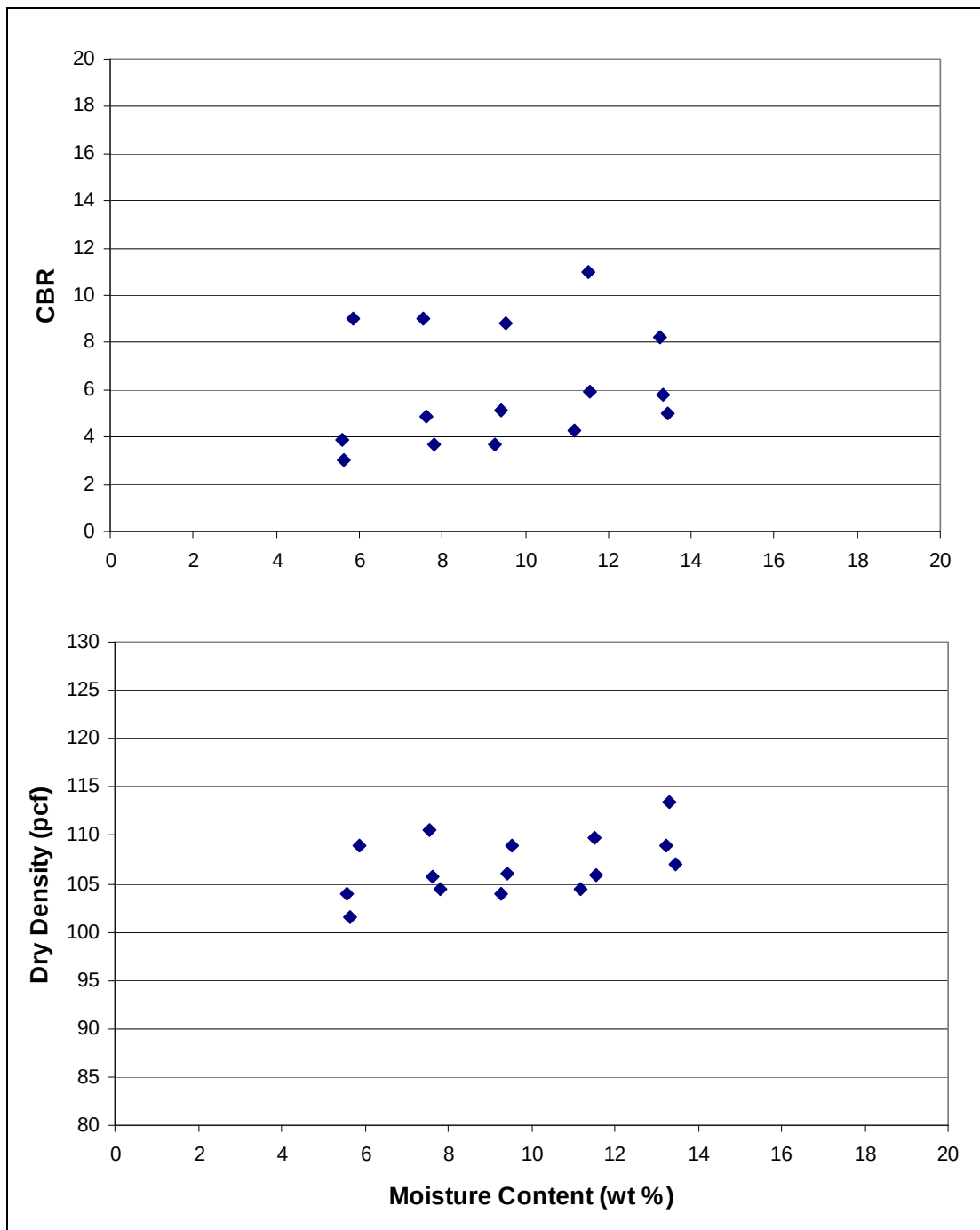


Figure B-2. CBR and dry density versus moisture content for low-density samples of El Centro soil.

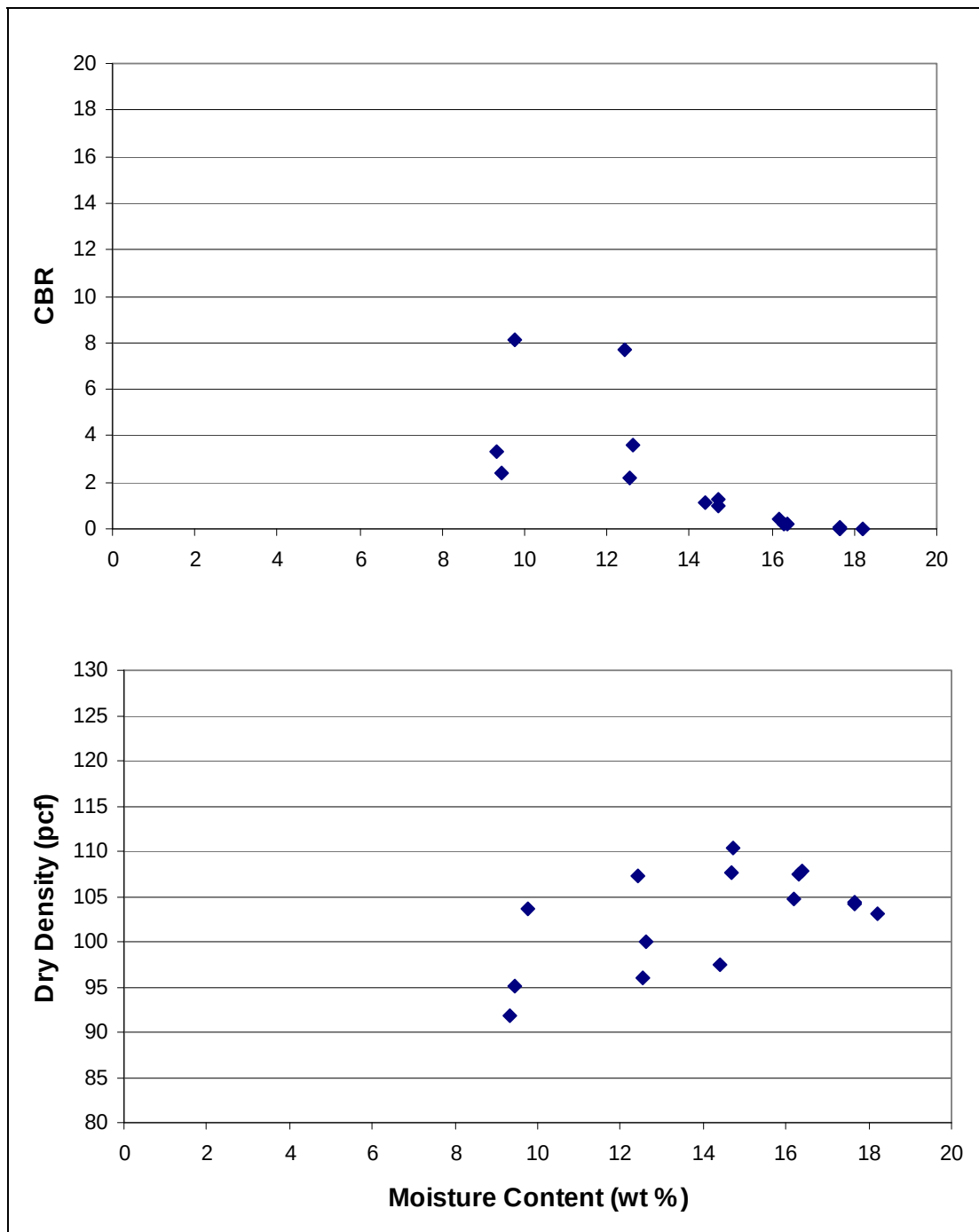


Figure B-3. CBR and dry density versus moisture content for low-density samples of Ford Farm soil.

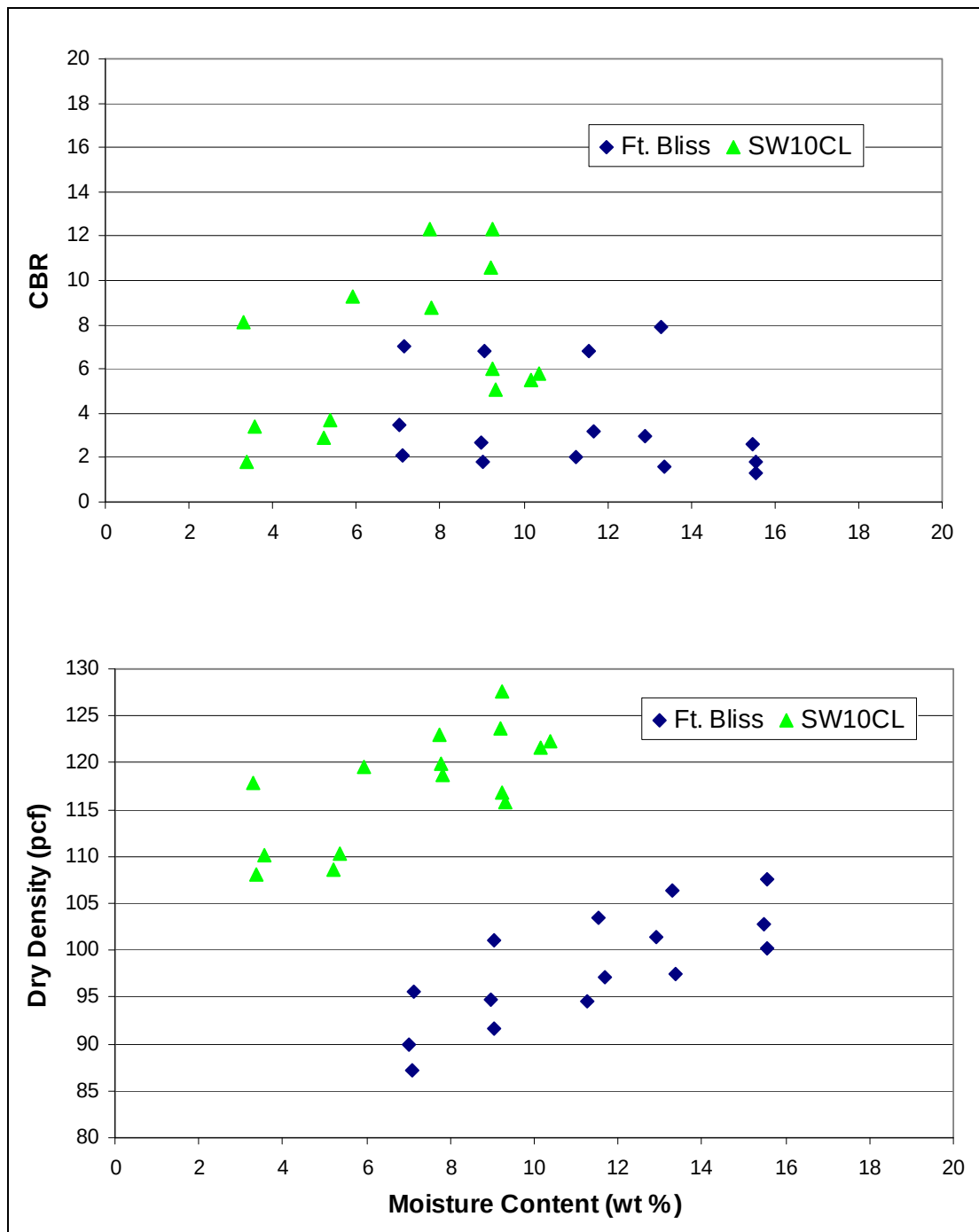


Figure B-4. CBR and dry density versus moisture content for low-density samples of SM soils.

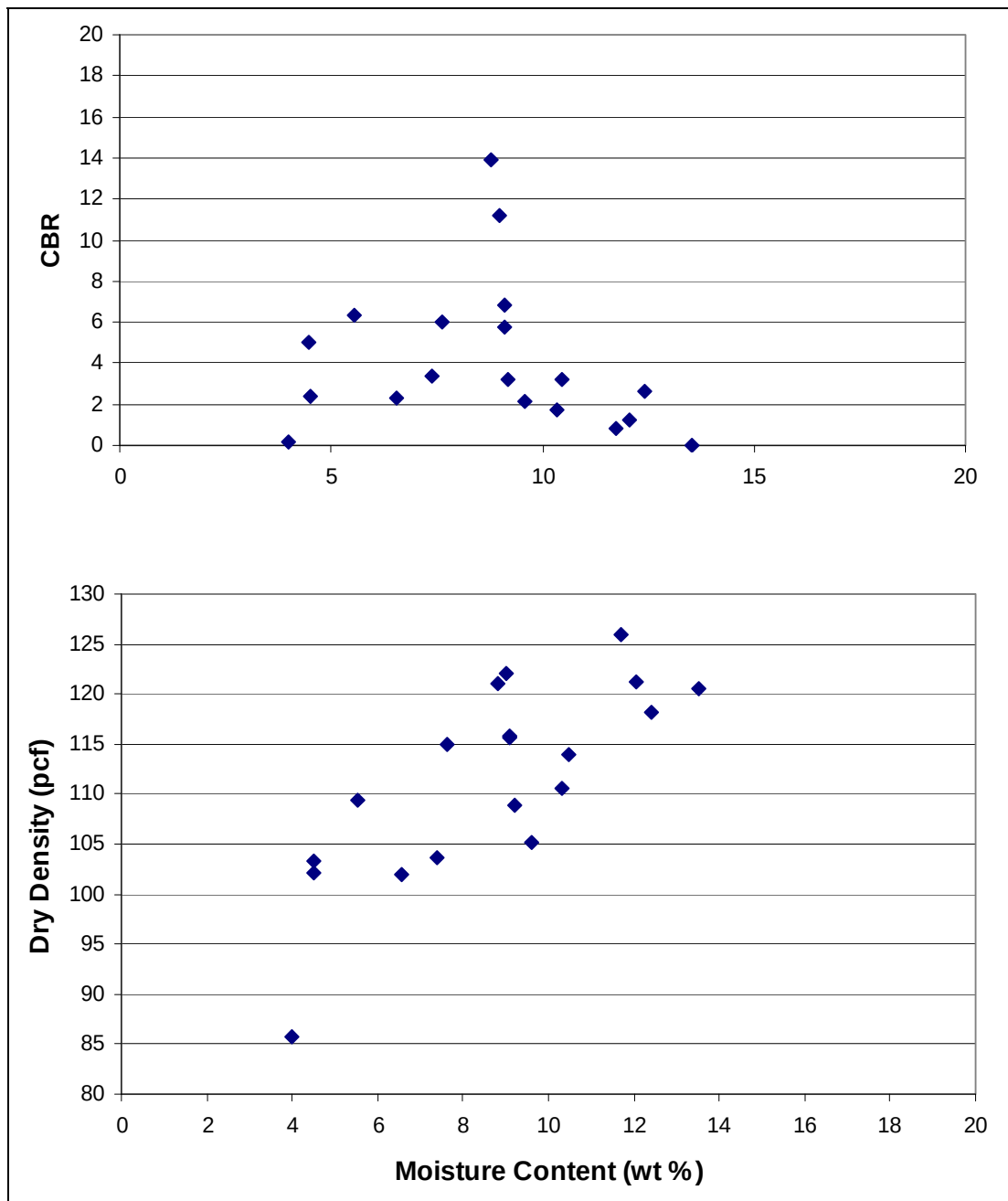


Figure B-5. CBR and dry density versus moisture content for low-density samples of SW30CL soil.

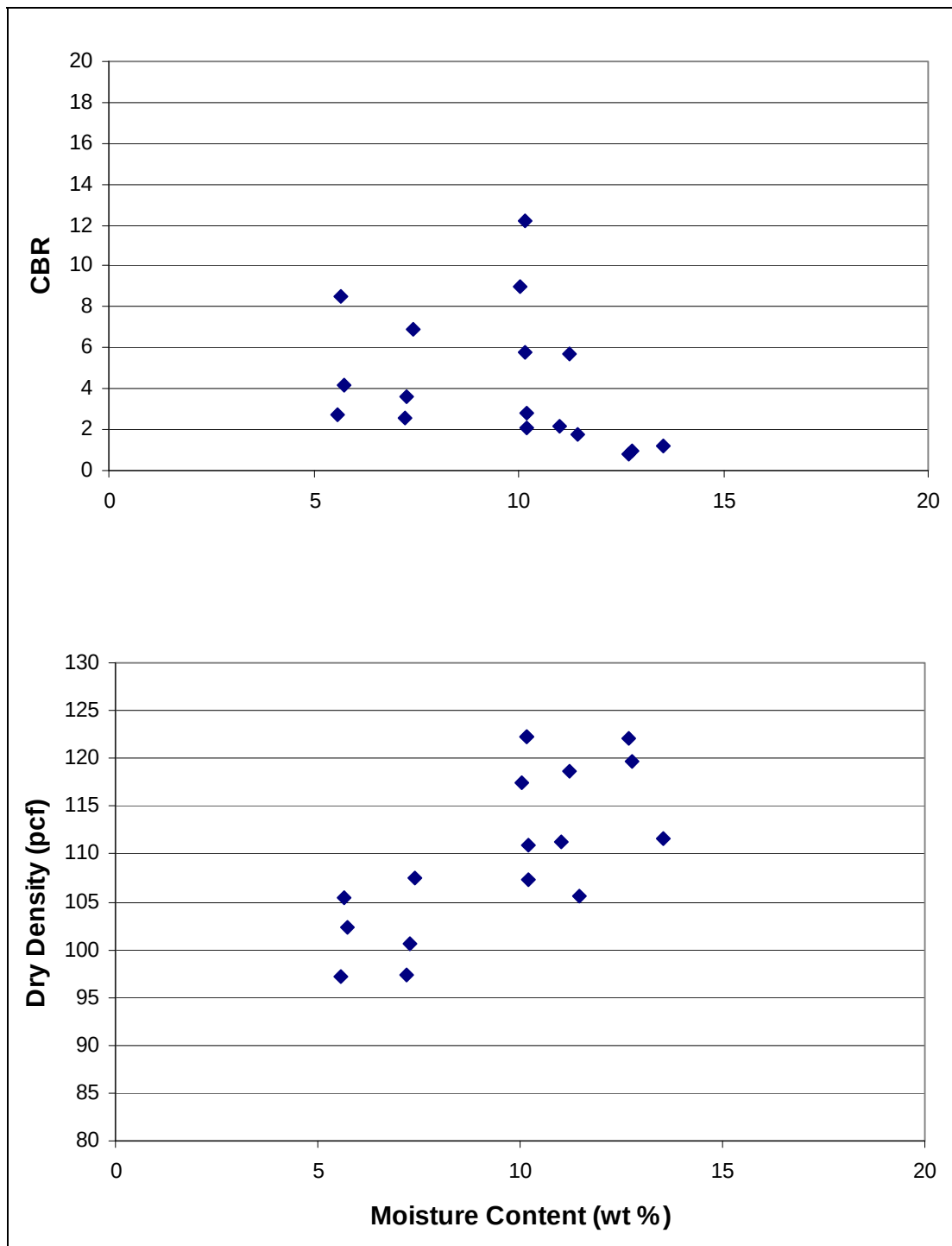


Figure B-6. CBR and dry density versus moisture content for low-density samples of SW40CL soil.

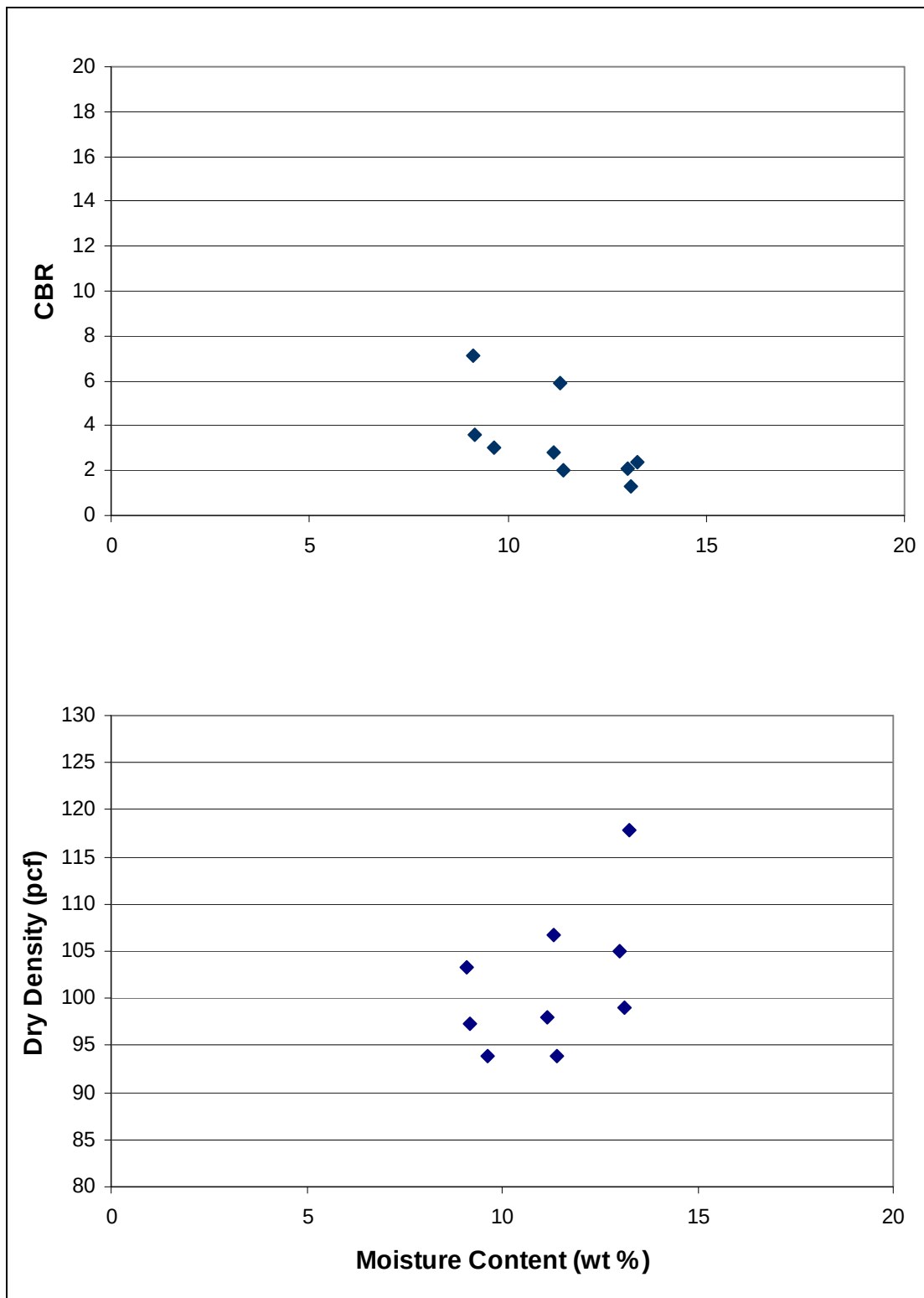


Figure B-7. CBR and dry density versus moisture content for low-density samples of SW60CL soil.

B2 CBR Versus Dry Density, Low-Density Samples

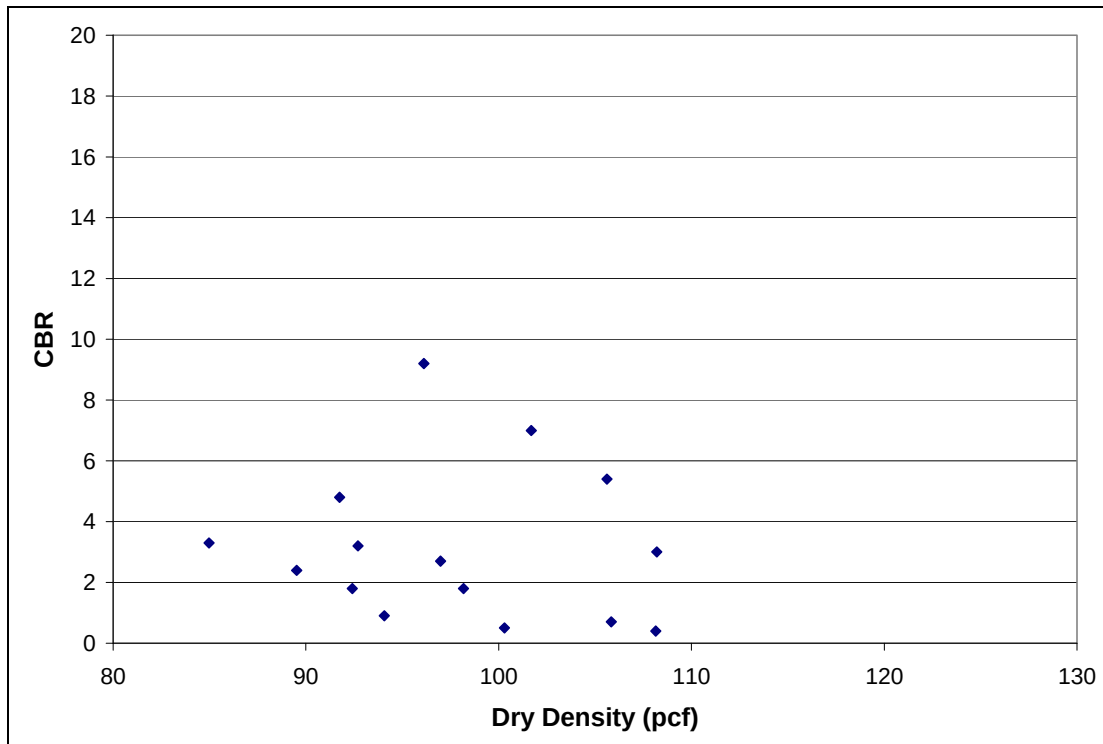


Figure B-8. CBR versus dry density for low-density samples of Cincinnati soil.

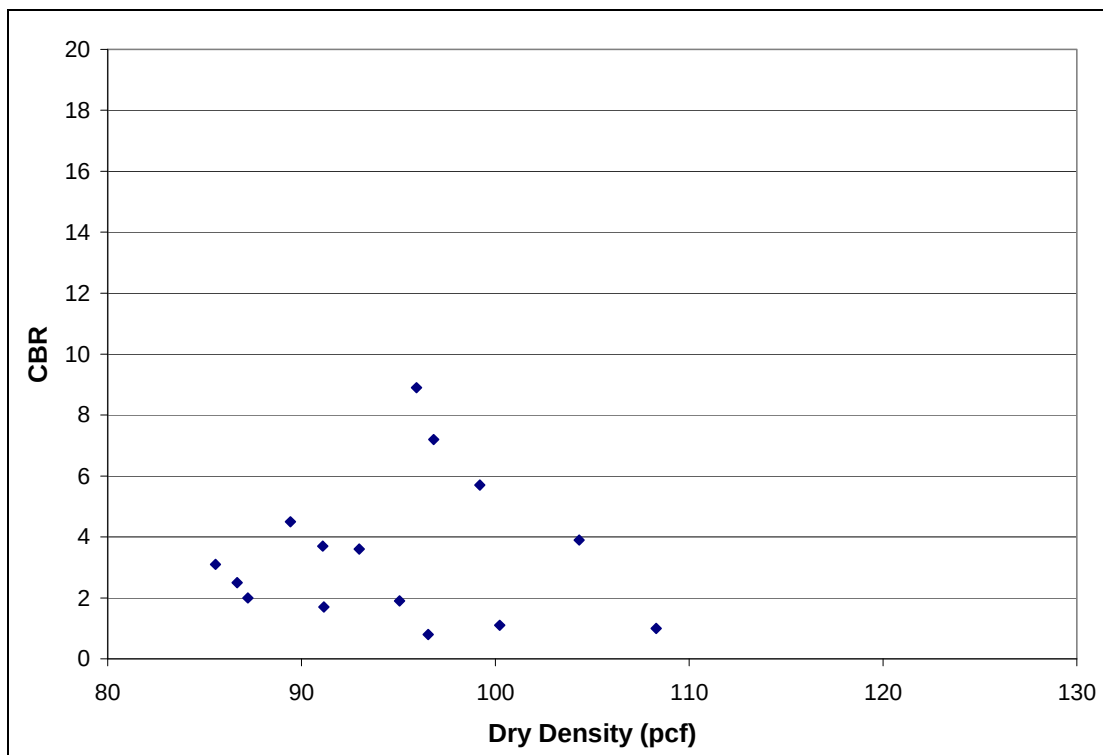


Figure B-9. CBR versus dry density for low-density samples of Cobb soil.

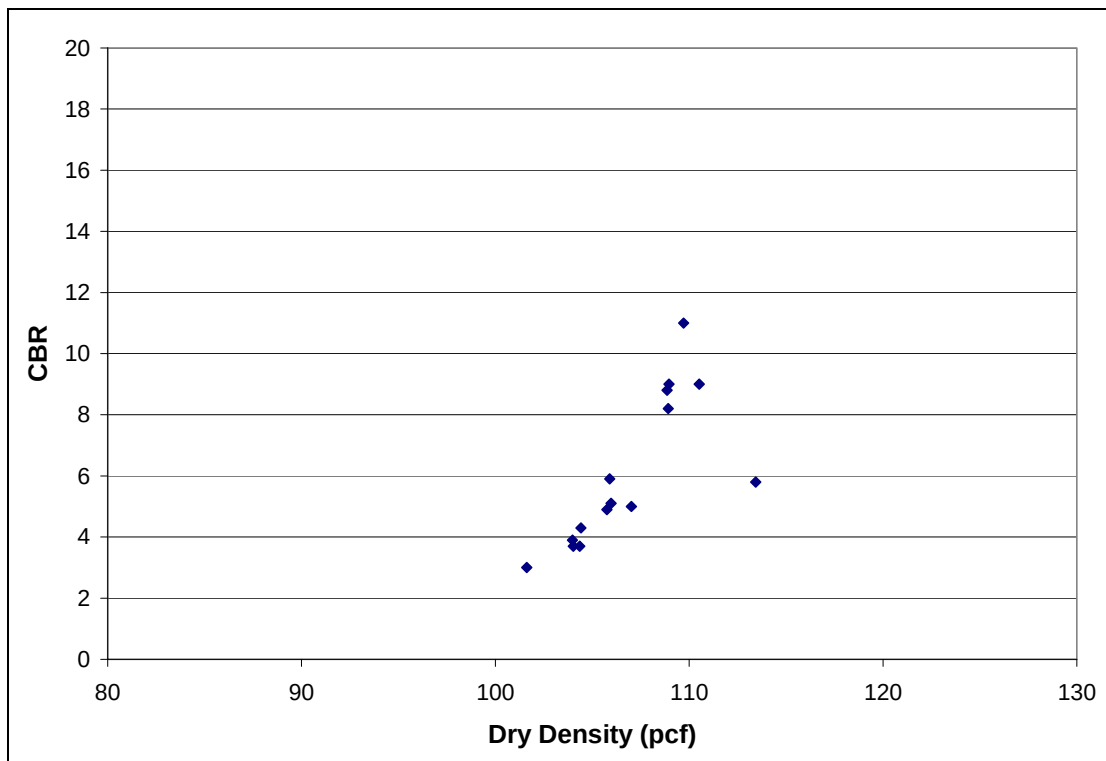


Figure B-10. CBR versus dry density for low-density samples of El Centro soil.

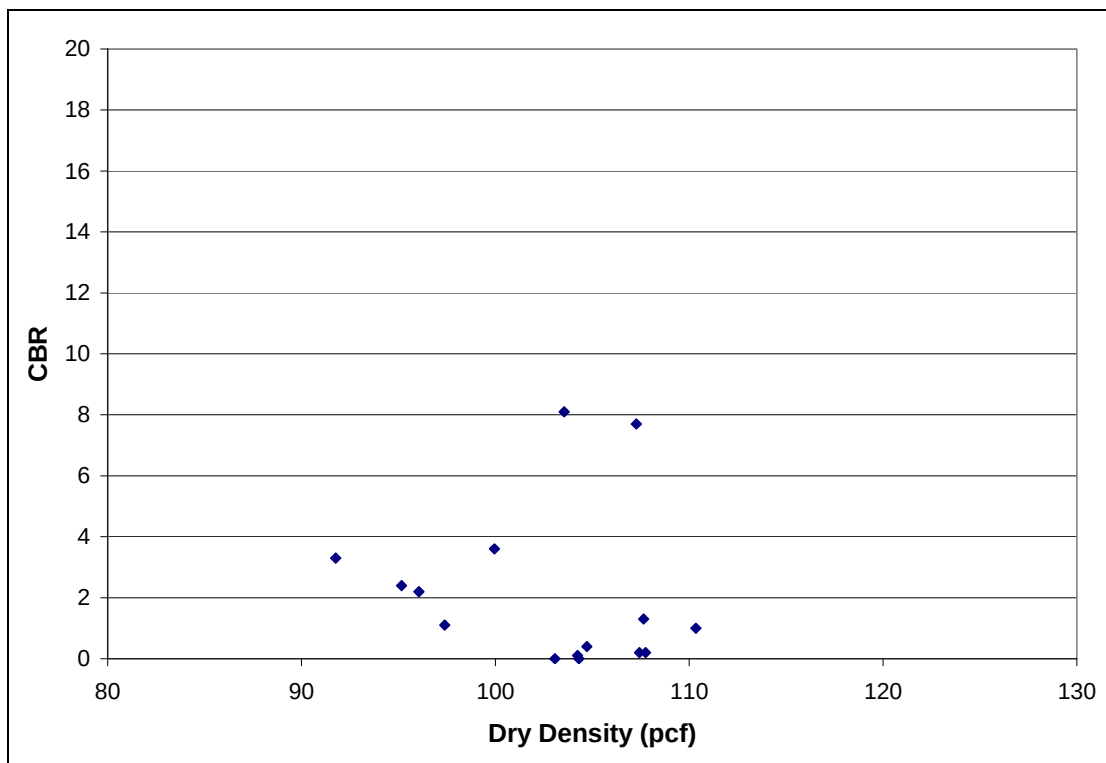


Figure B-11. CBR versus dry density for low-density samples of Ford Farm soil.

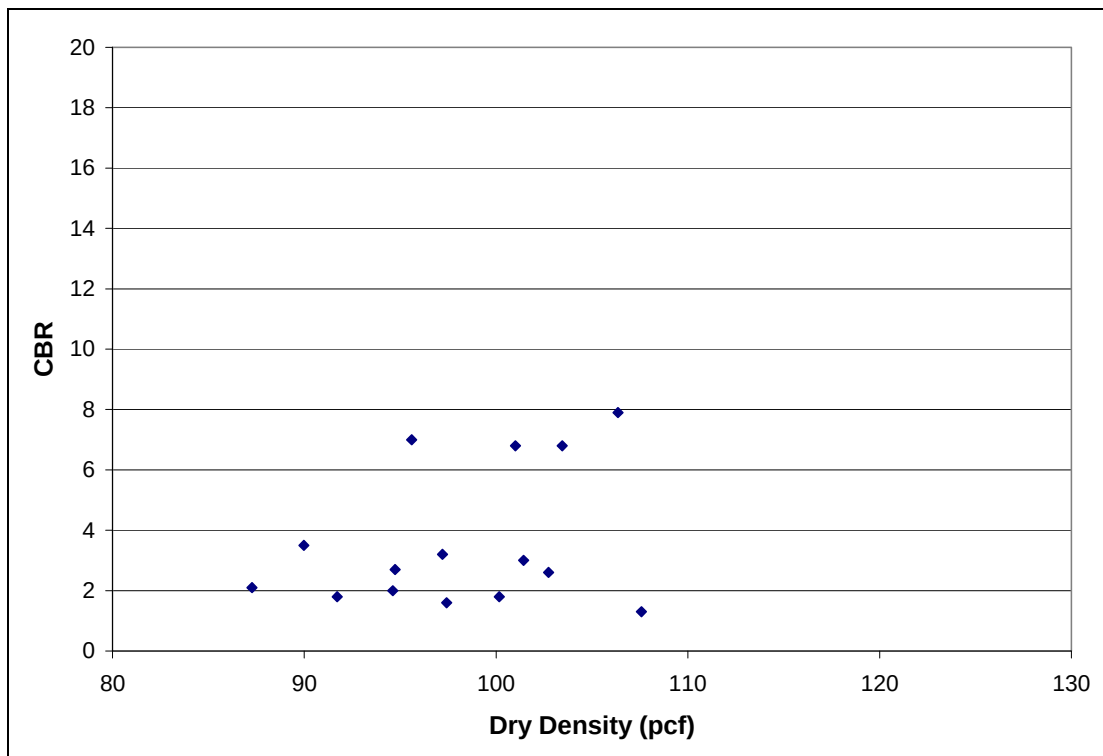


Figure B-12. CBR versus dry density for low-density samples of Fort Bliss soil.

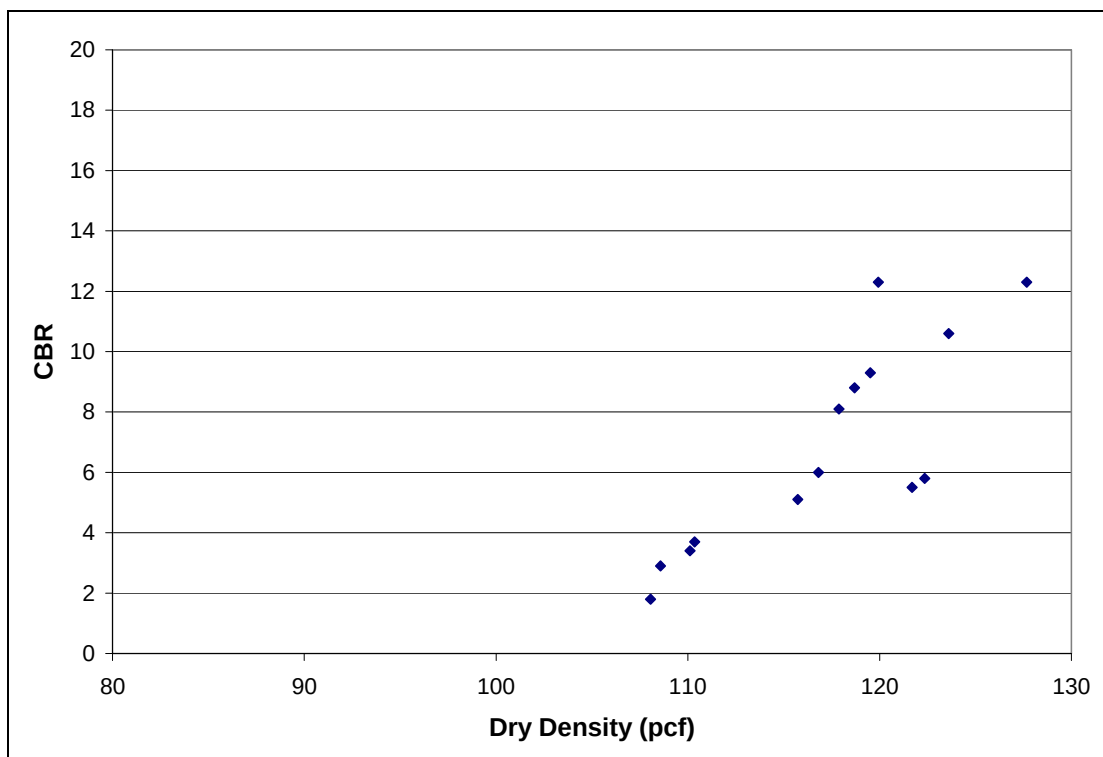


Figure B-13. CBR versus dry density for low-density samples of SW10CL soil combination.

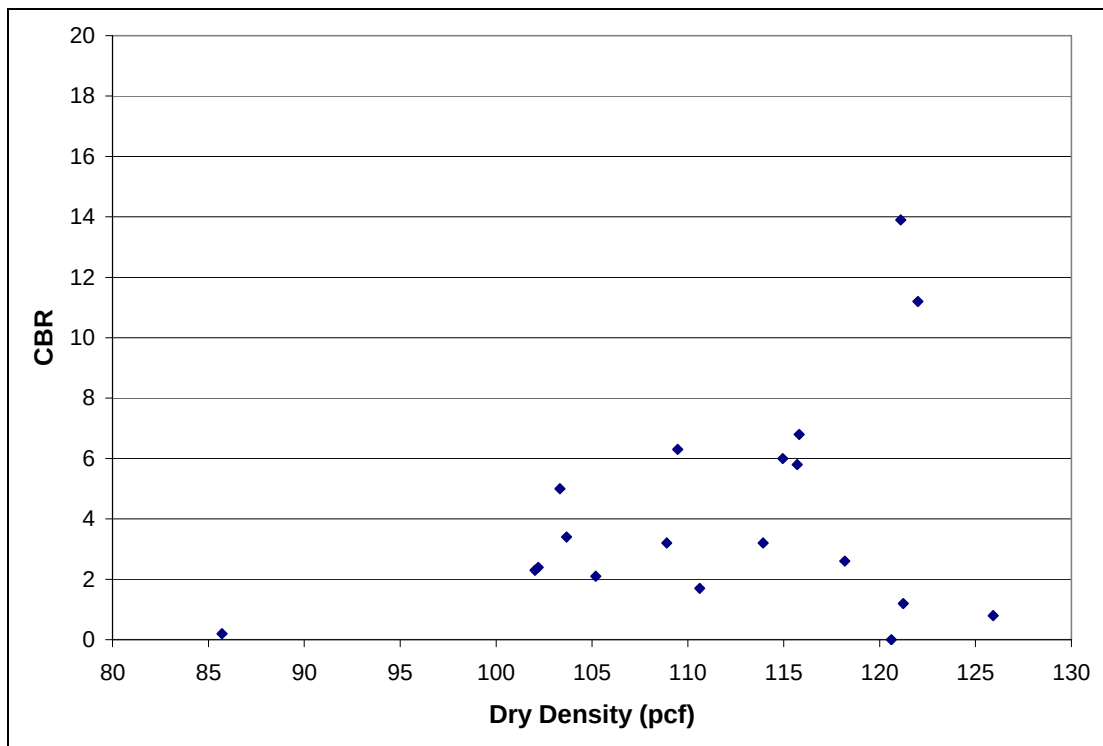


Figure B-14. CBR versus dry density for low-density samples of SW30CL soil combination.

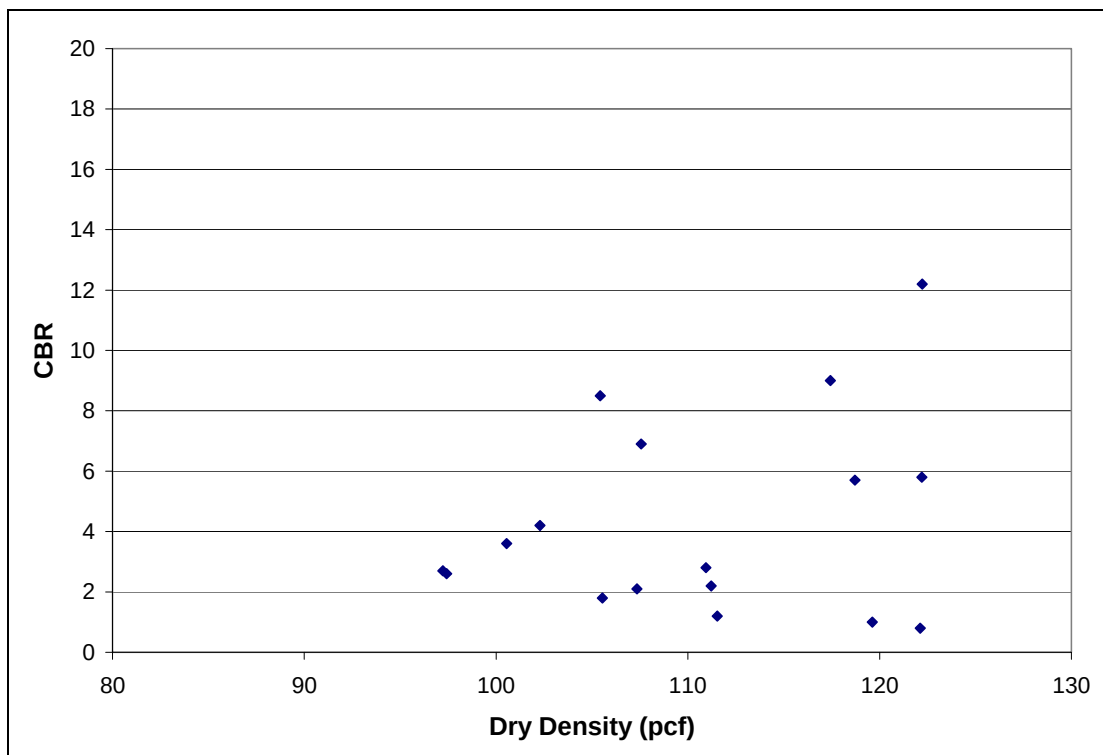


Figure B-15. CBR versus dry density for low-density samples of SW40CL soil combination.

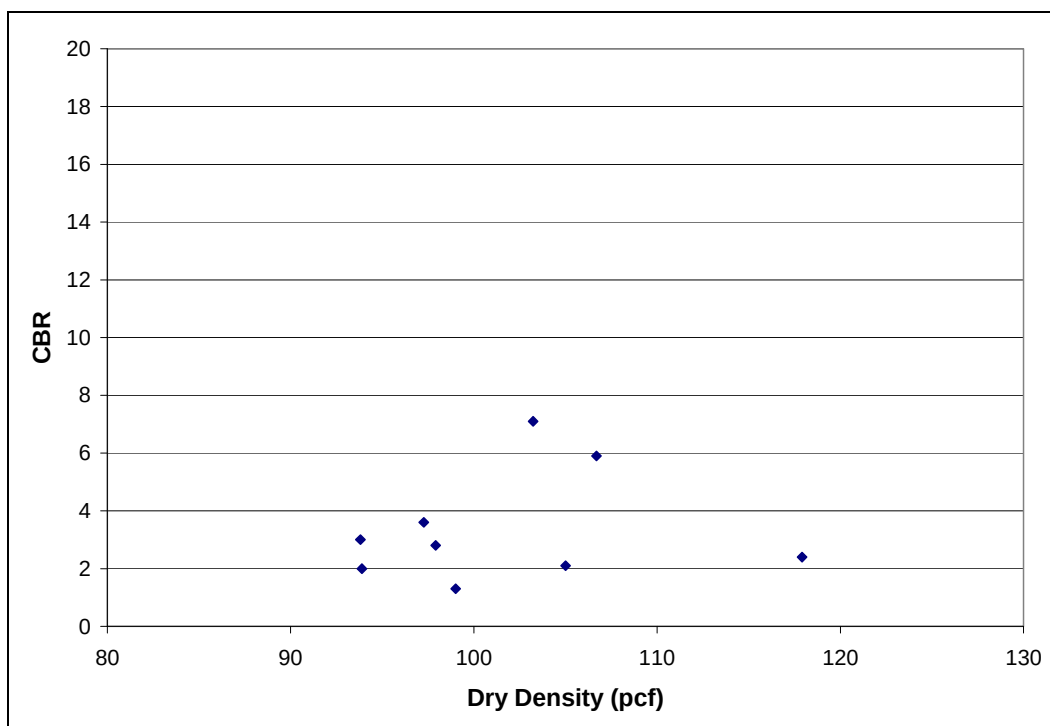


Figure B-16. CBR versus dry density for low-density samples of SW60CL soil combination.

B3 CBR Variation with Moisture Content

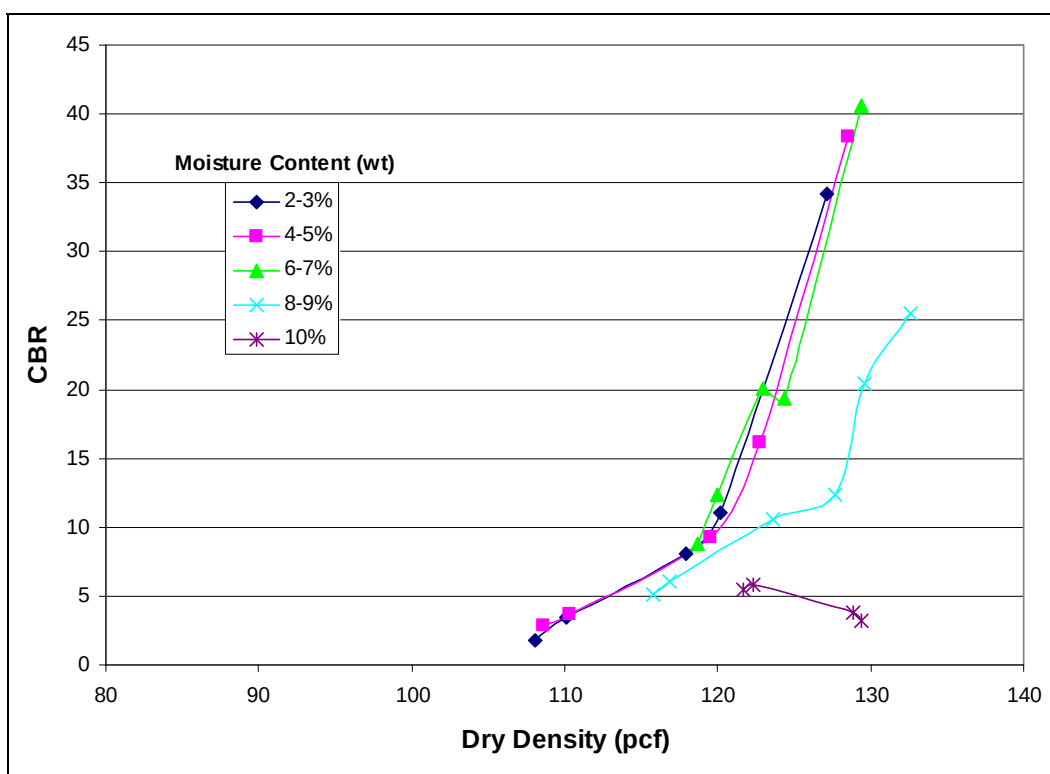


Figure B-17. Variation in CBR versus dry density with moisture content for SW10CL soil combination.

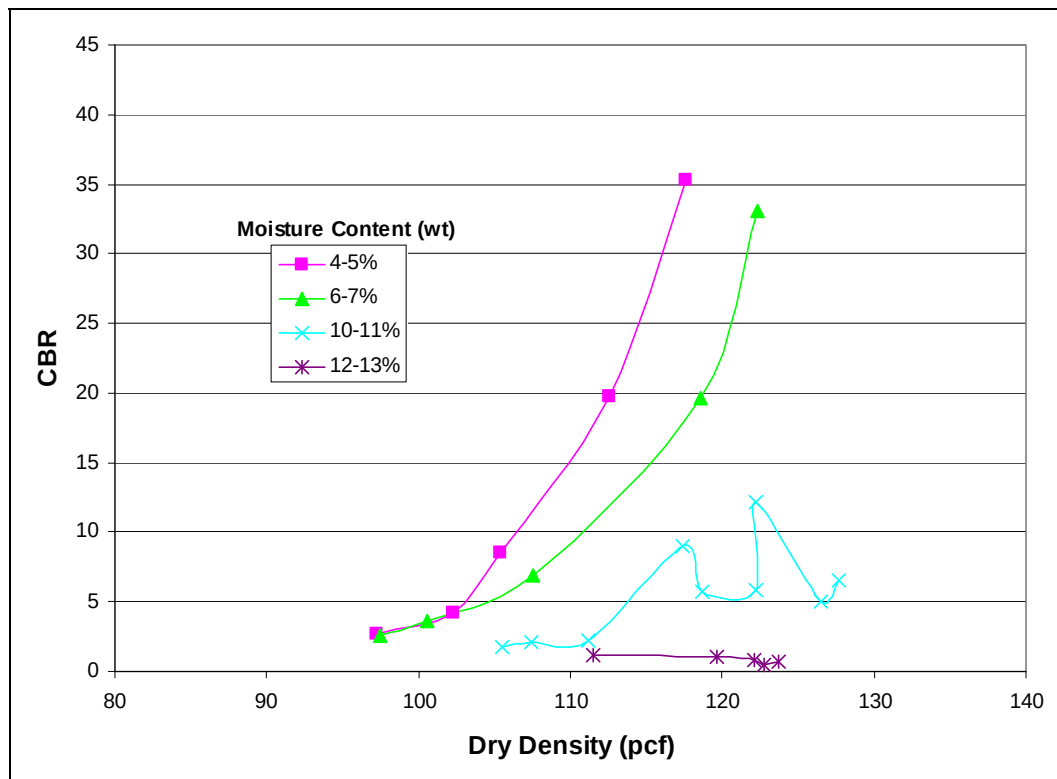


Figure B-18. Variation in CBR versus dry density with moisture content for SW40CL soil combination.

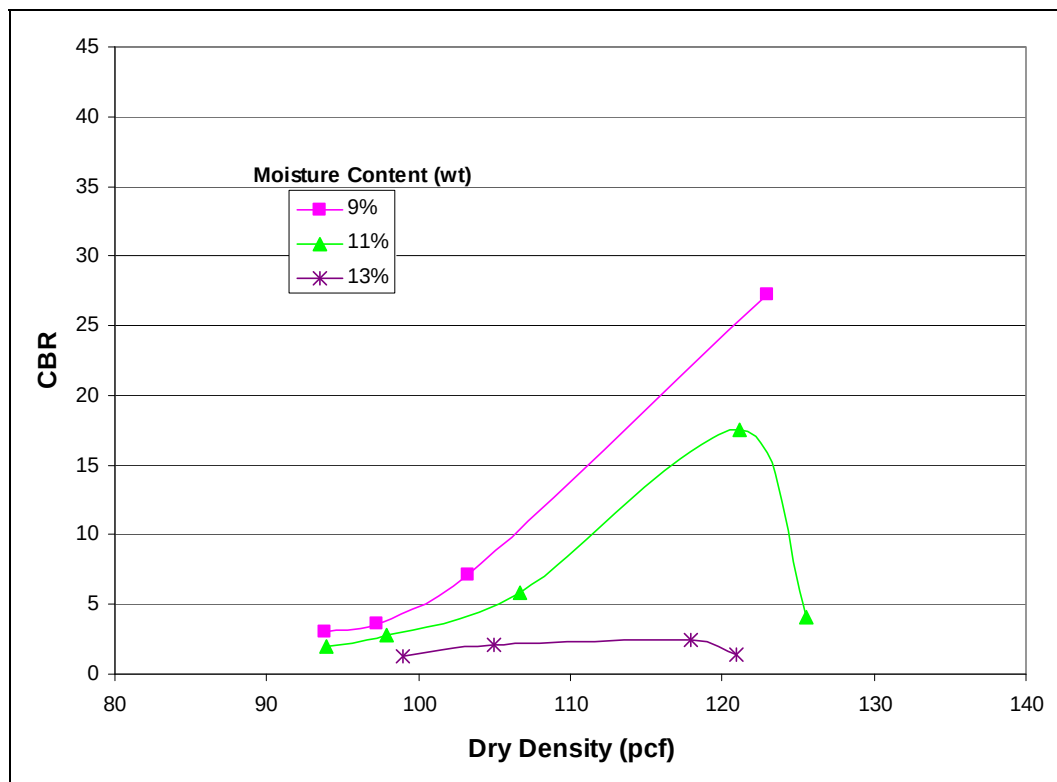


Figure B-19. Variation in CBR versus dry density with moisture content for SW60CL soil combination.

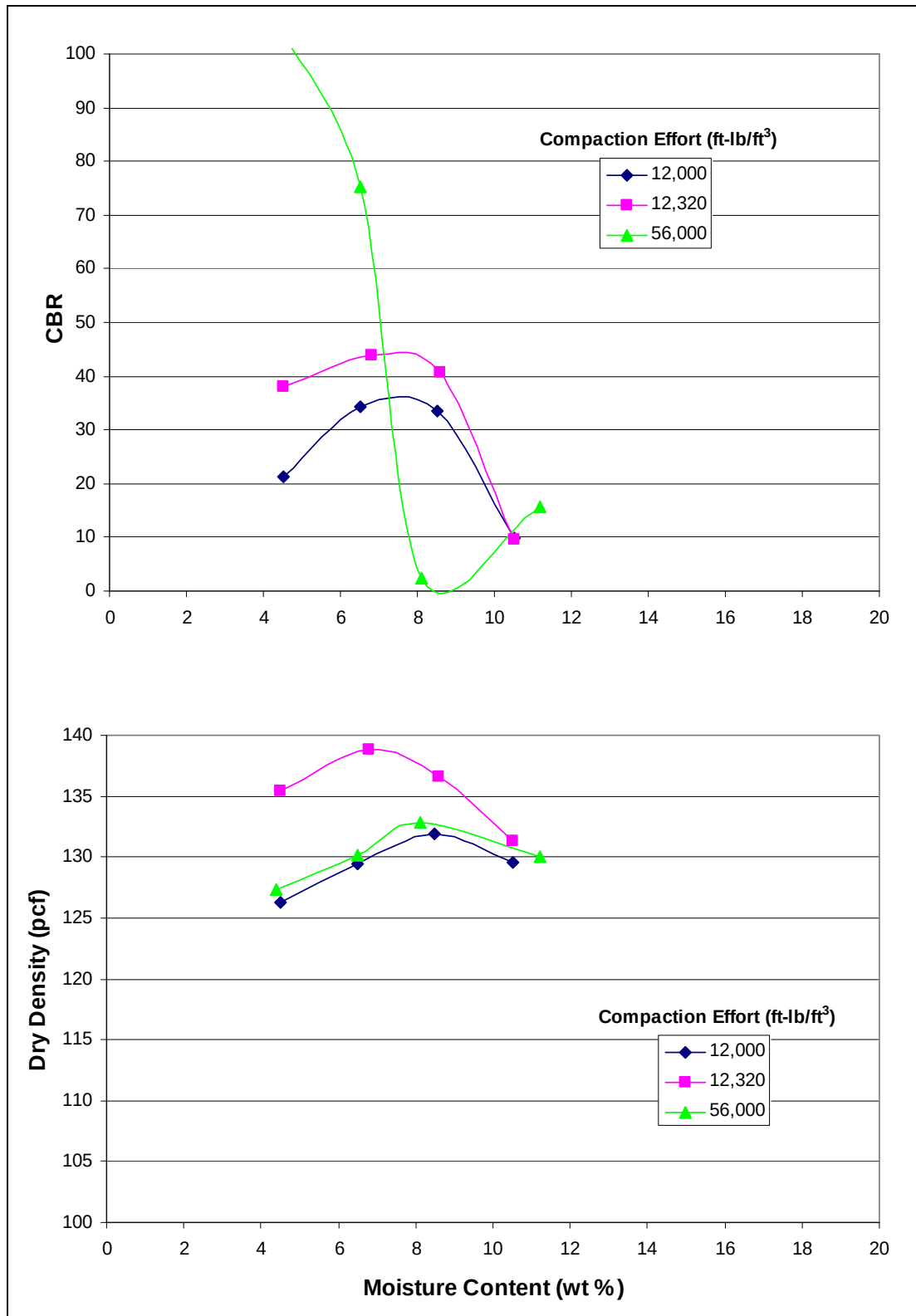
B4 CBR Variation with Compaction Effort

Figure B-20. CBR variation with compaction effort for SP5CH soil combination.

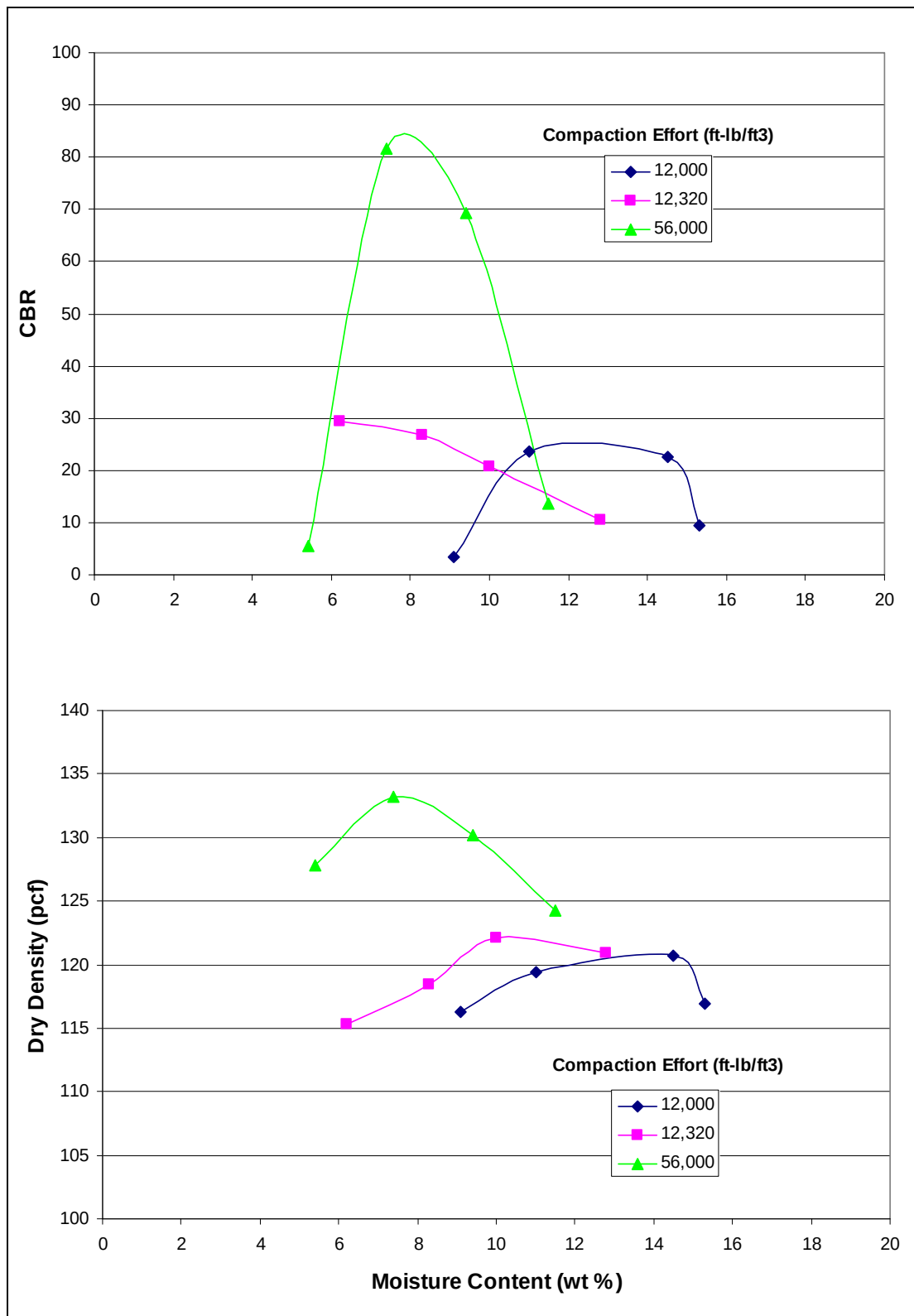


Figure B-21. CBR variation with compaction effort for SP25CH soil combination.

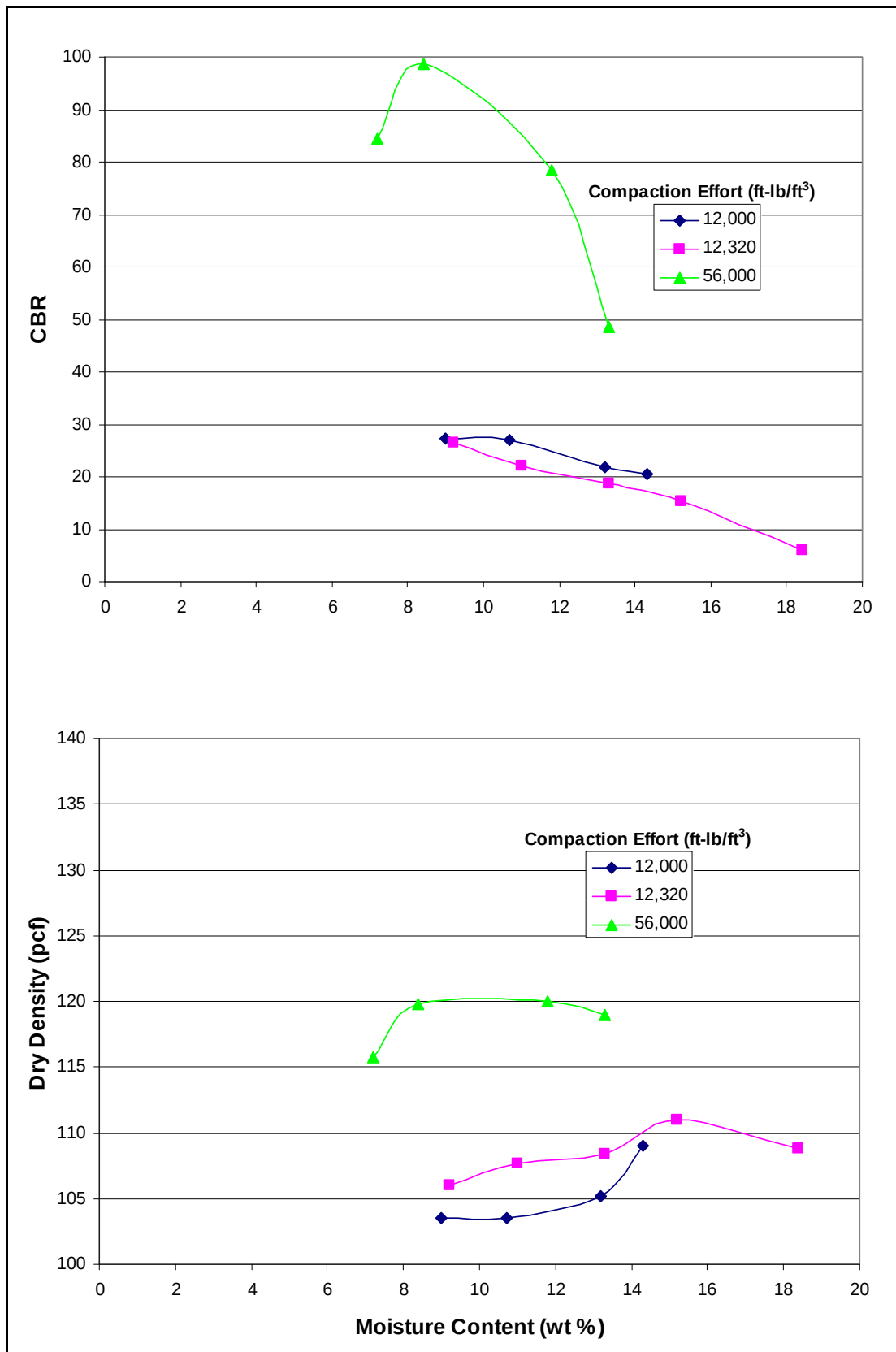


Figure B-22. CBR variation with compaction effort for SP45CH soil combination.

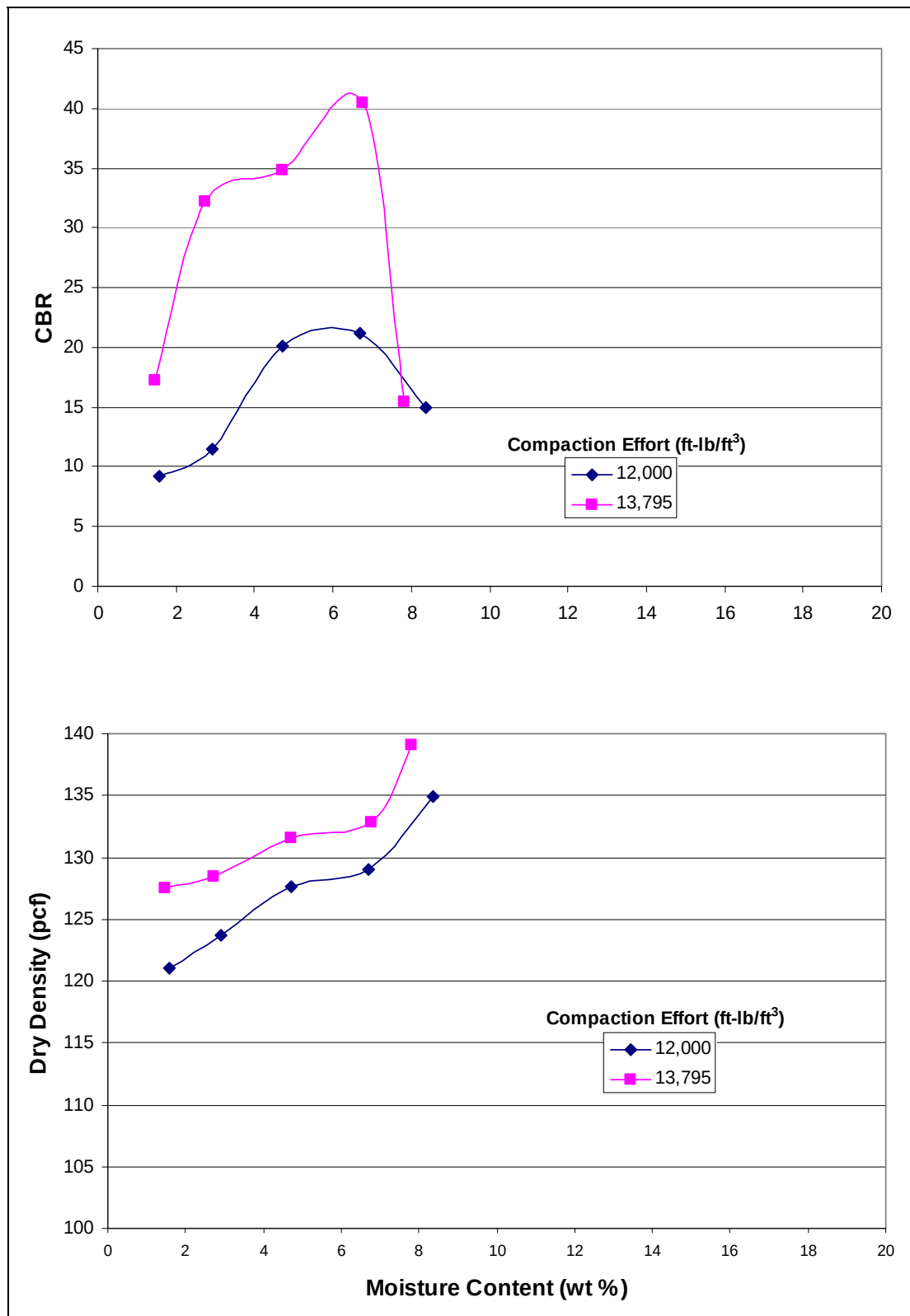


Figure B-23. CBR variation with compaction effort for SP9CL soil combination.

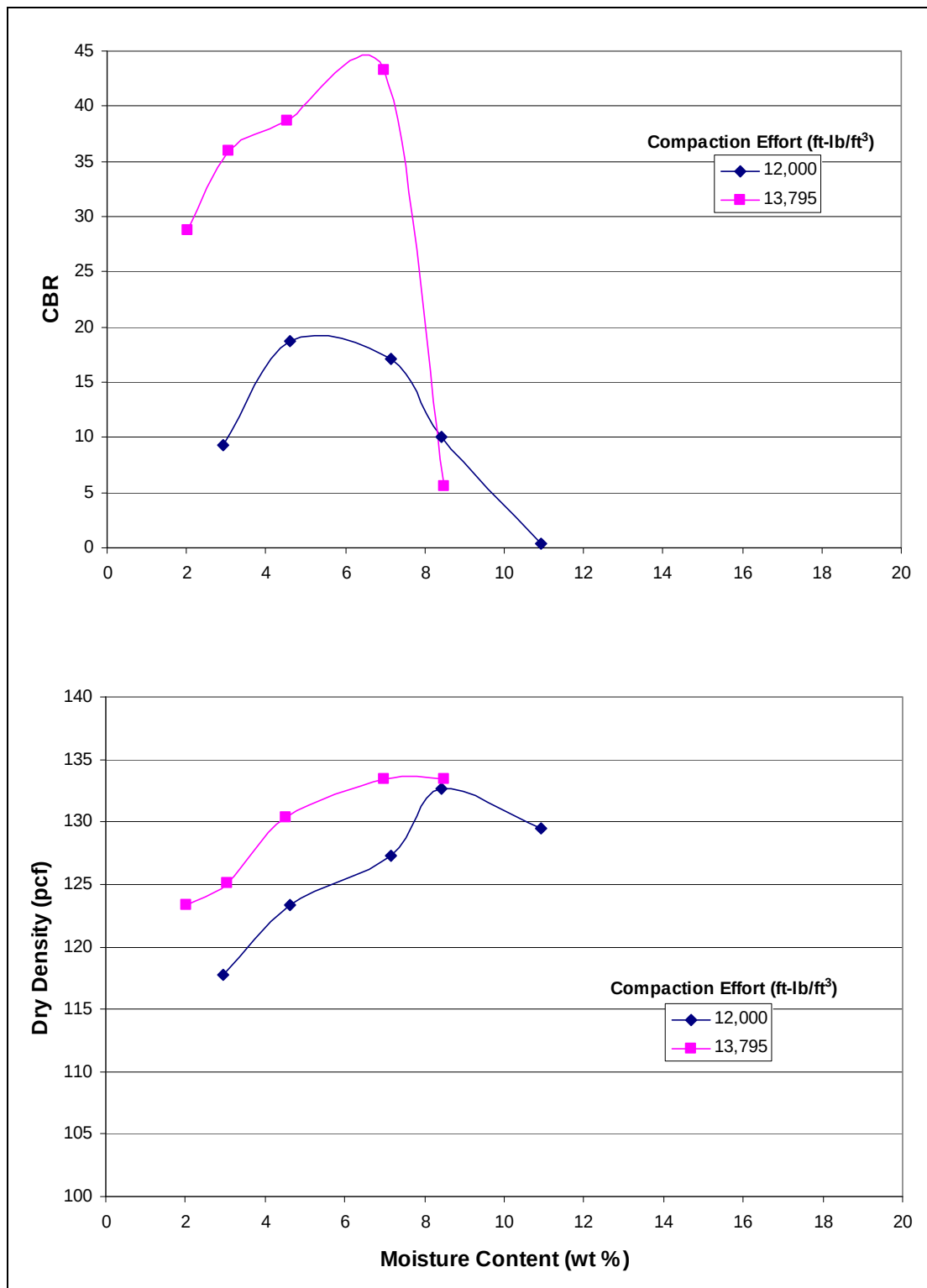


Figure B-24. CBR variation with compaction effort for SP23CL soil combination.

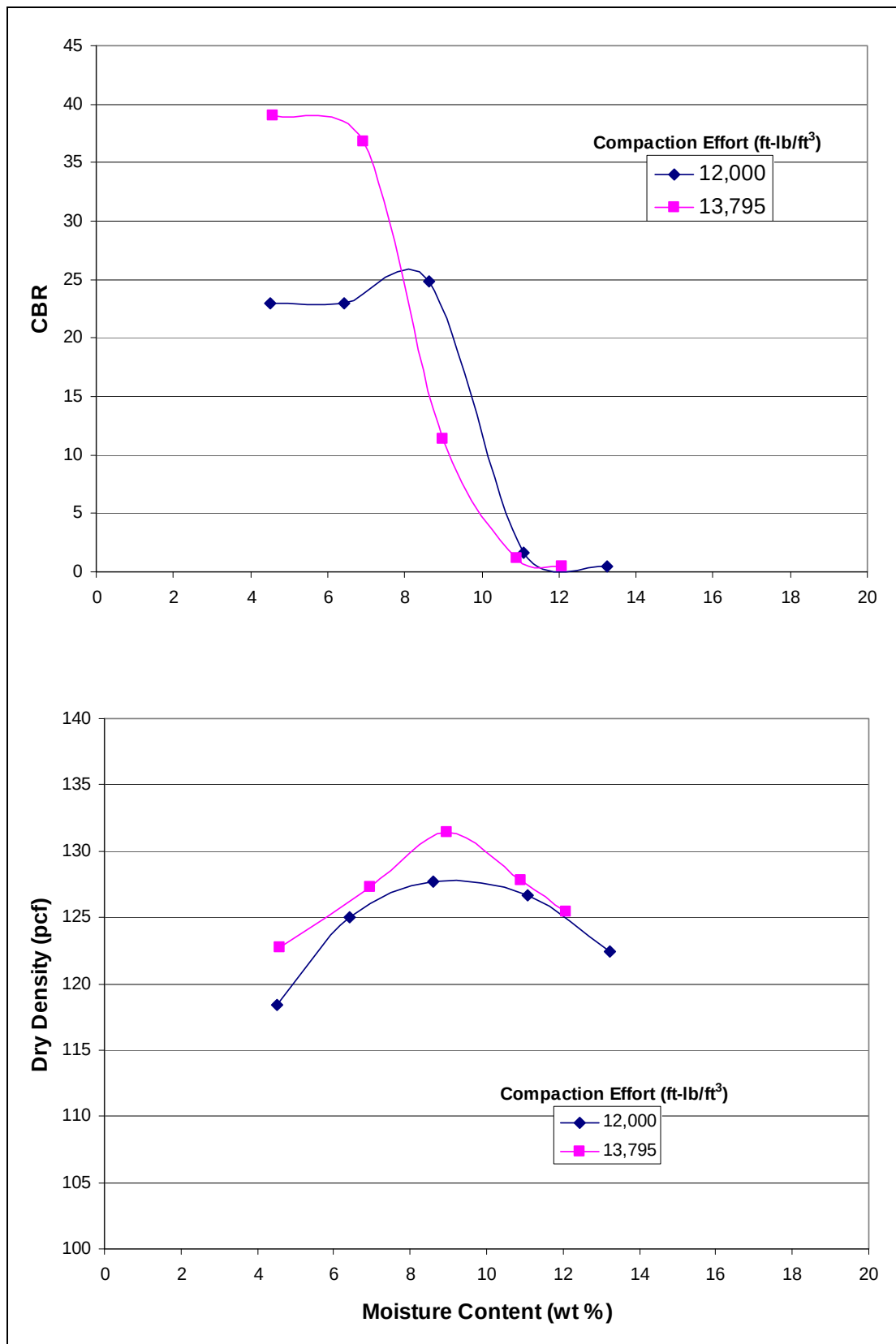


Figure B-25. CBR variation with compaction effort for SP35CL soil combination.

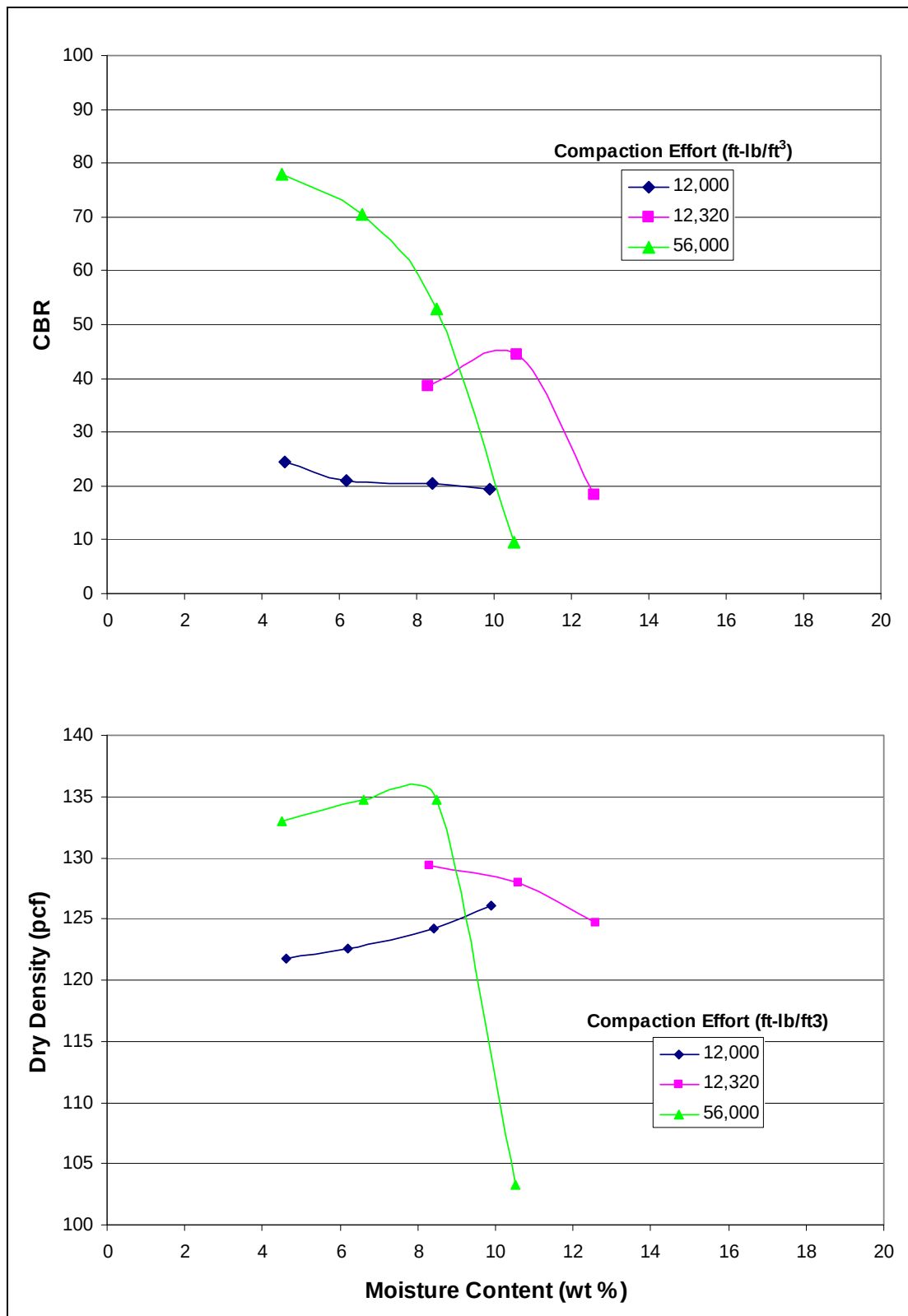


Figure B-26. CBR variation with compaction effort for SW5CH soil combination.

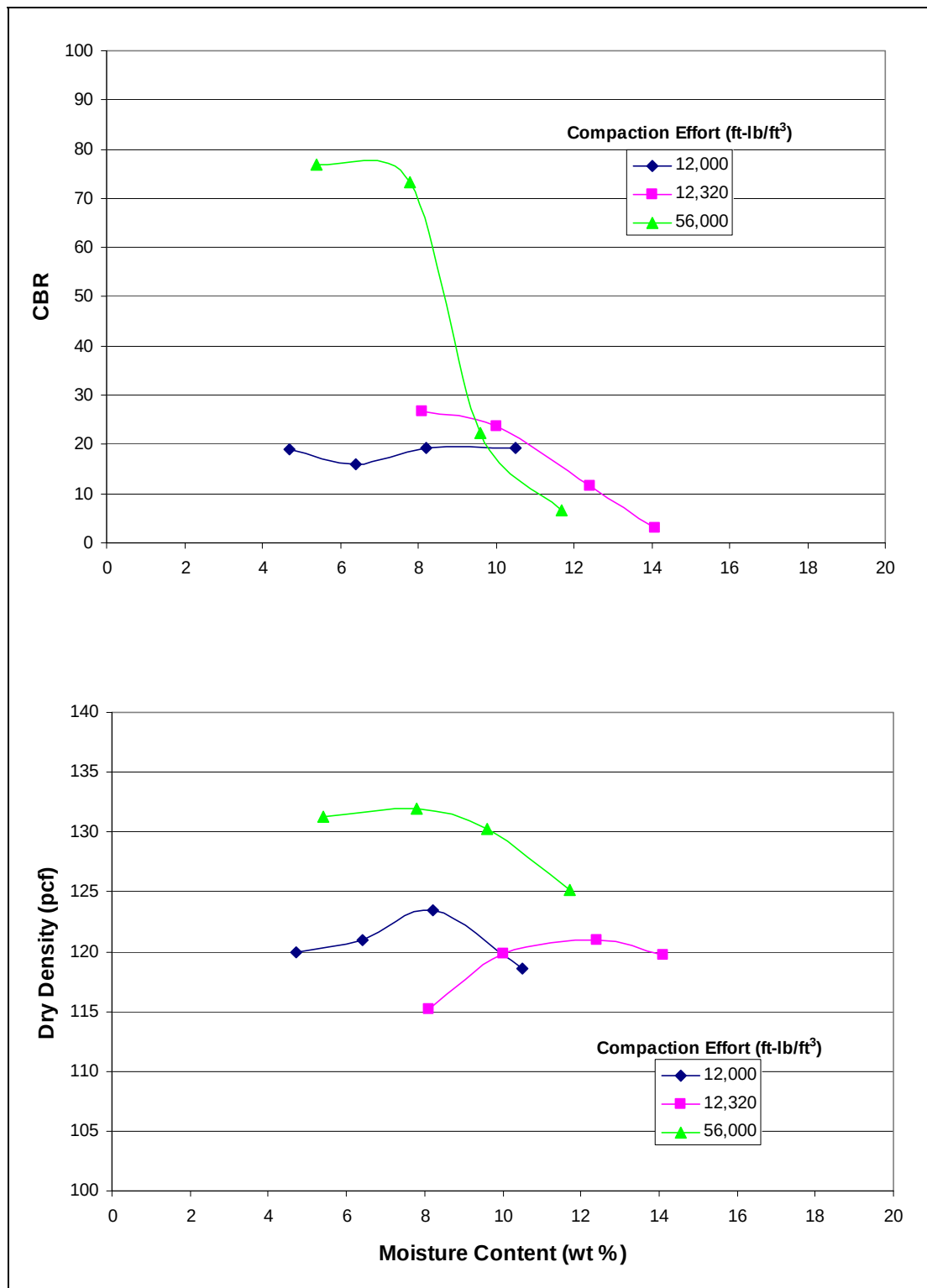


Figure B-27. CBR variation with compaction effort for SW25CH soil combination.

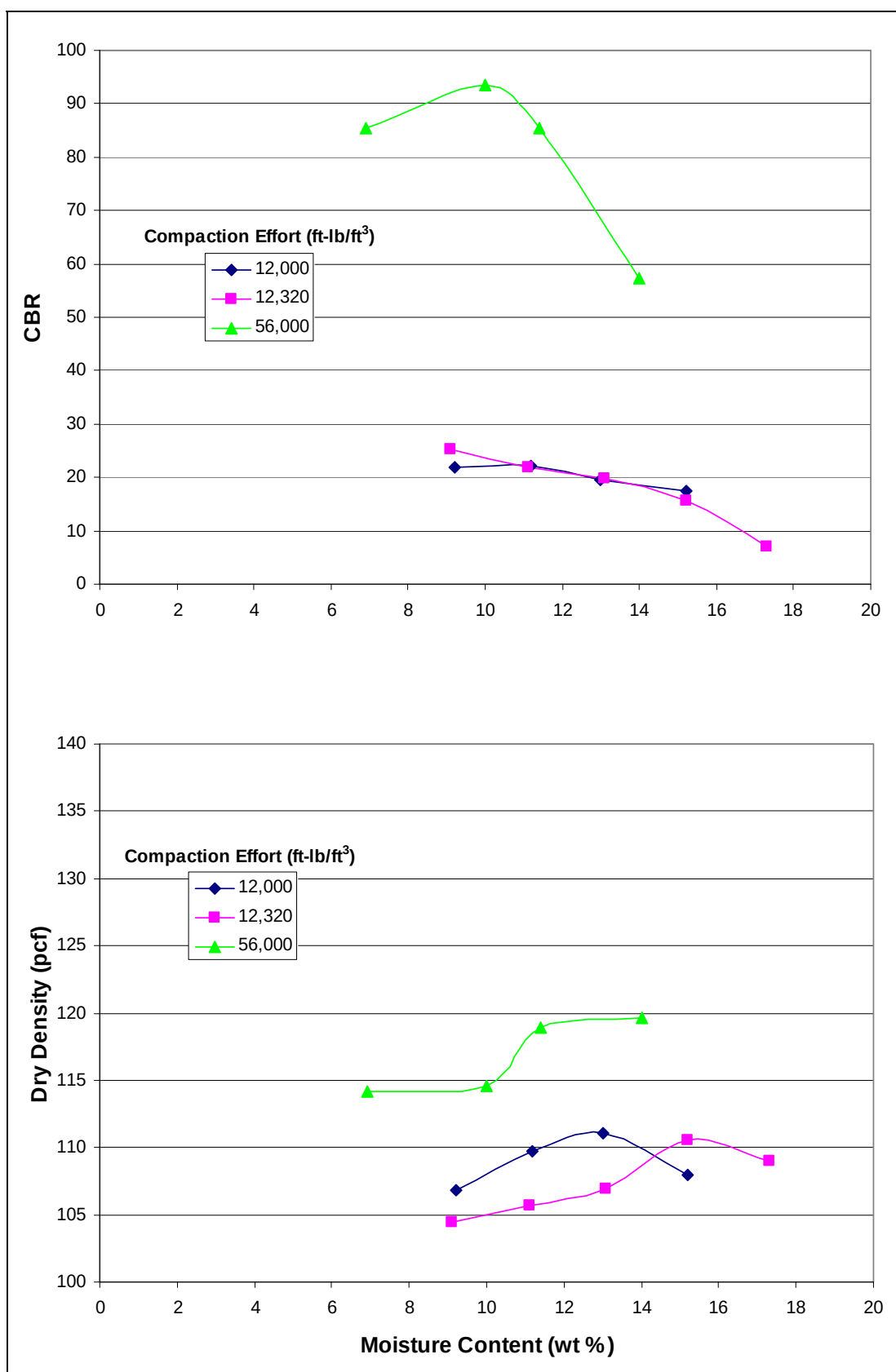


Figure B-28. CBR variation with compaction effort for SW45CH soil combination.

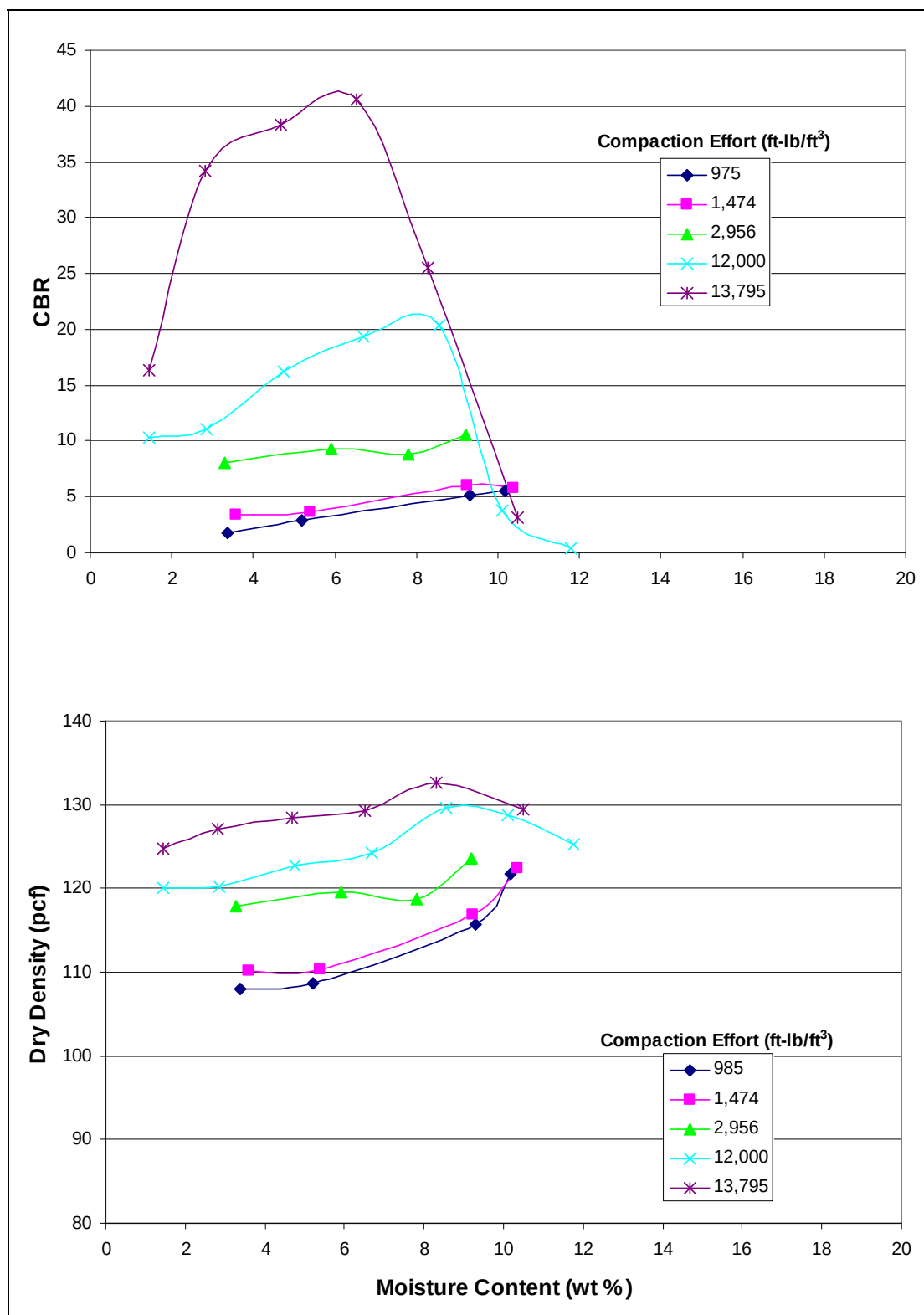


Figure B-29. CBR variation with compaction effort for SW10CL soil combination.

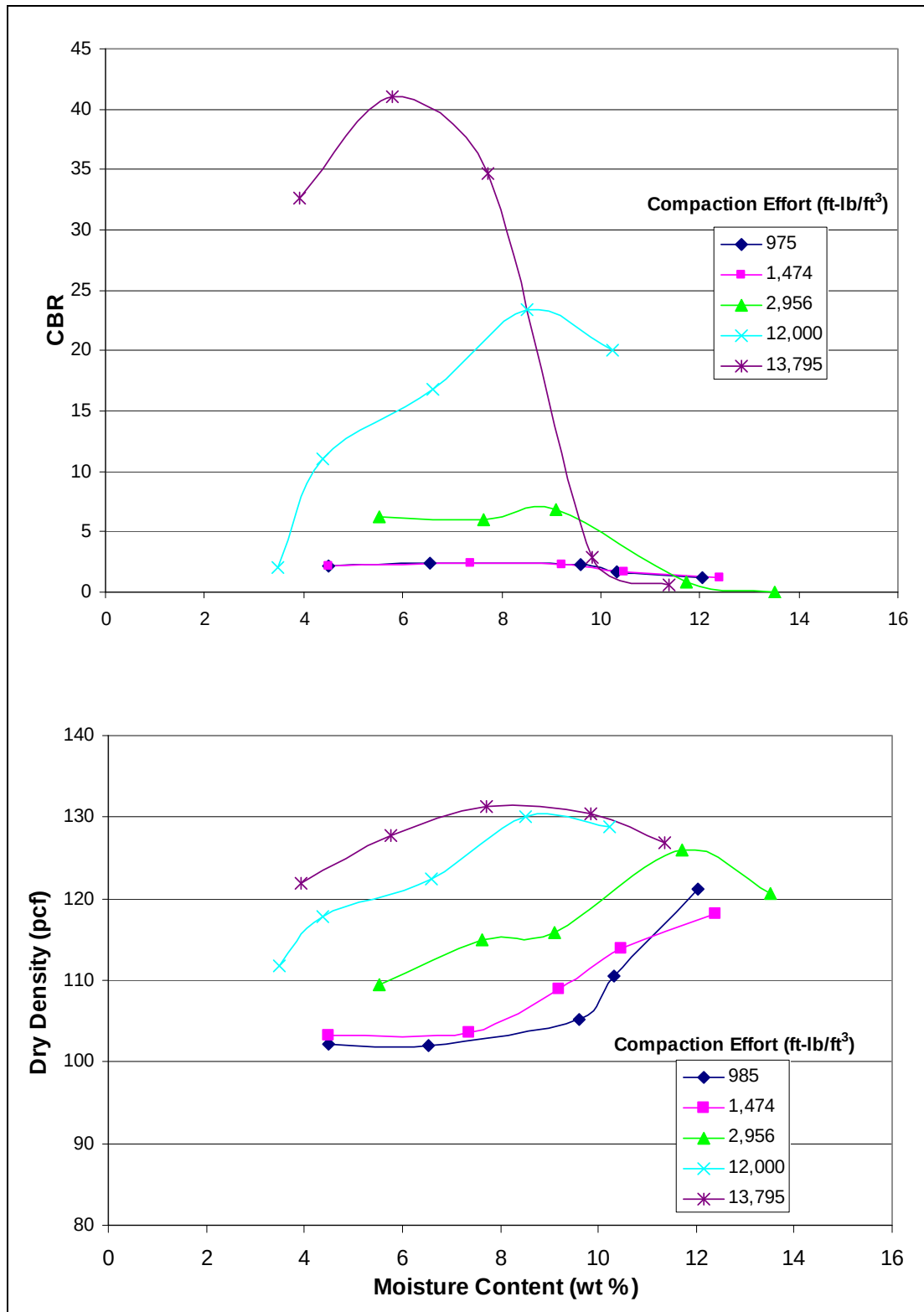


Figure B-30. CBR variation with compaction effort for SW30CL soil combination.

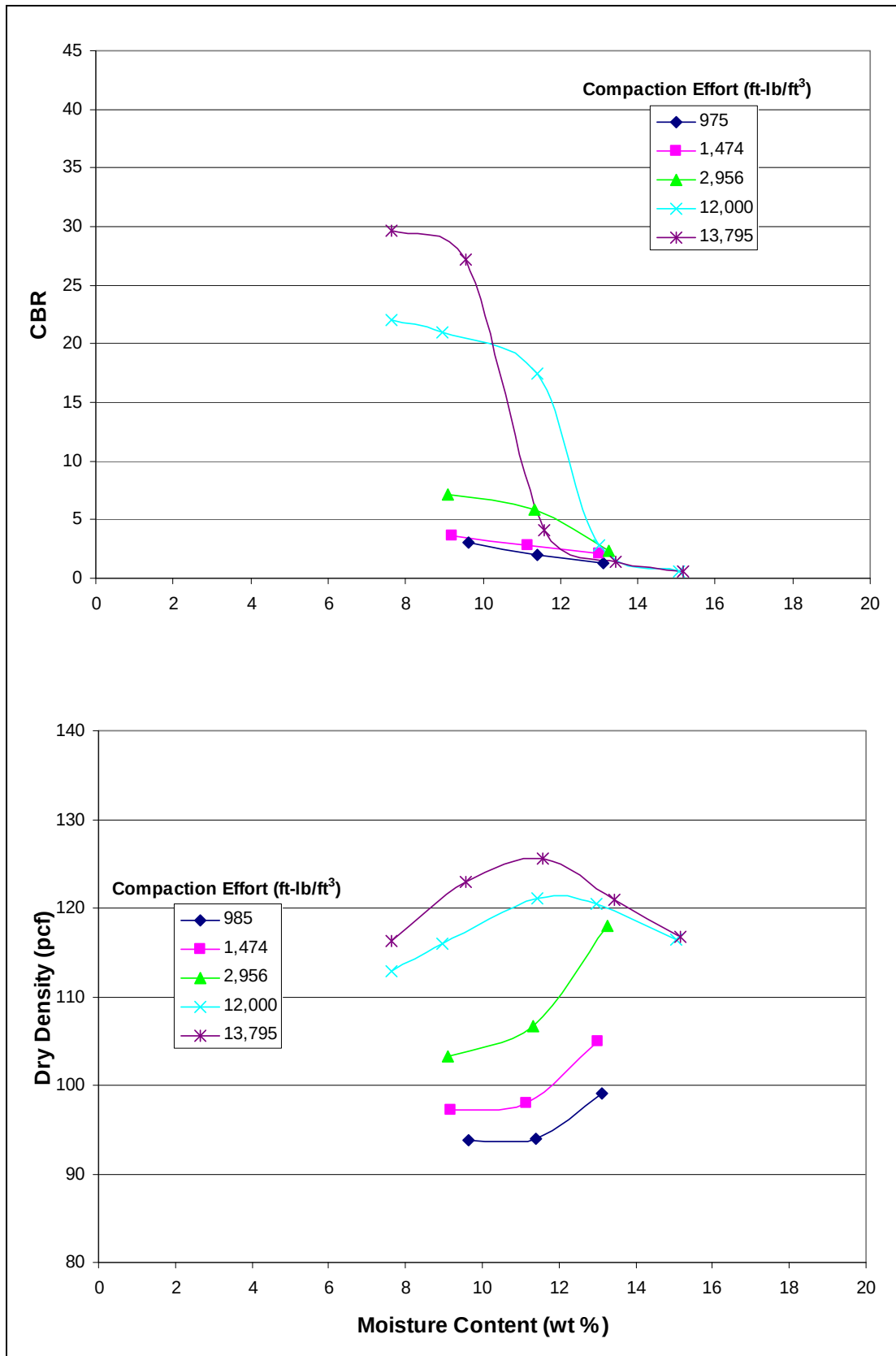


Figure B-31. CBR variation with compaction effort for SW40CL soil combination.

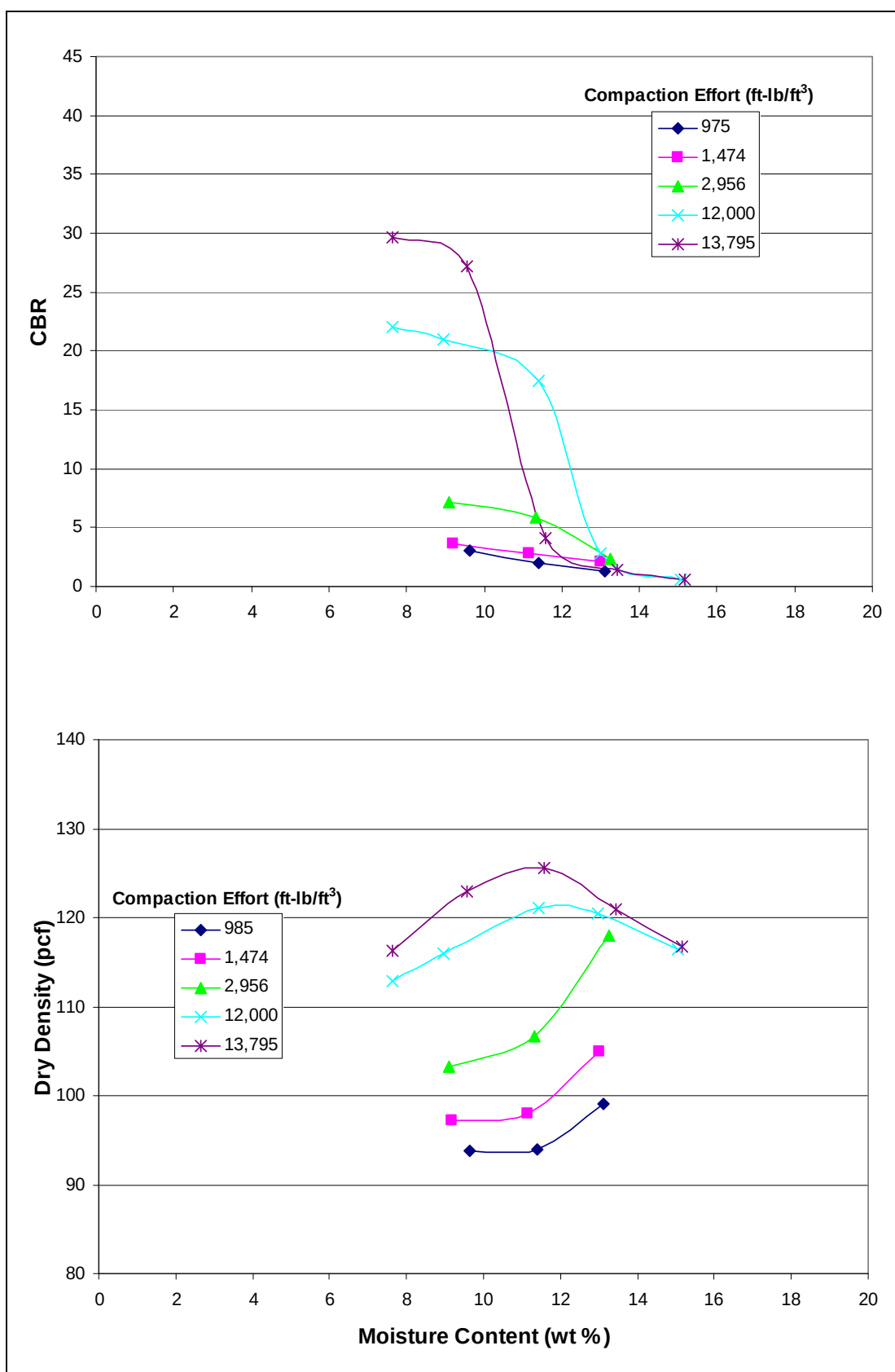


Figure B-32. CBR variation with compaction effort for SW60CL soil combination.

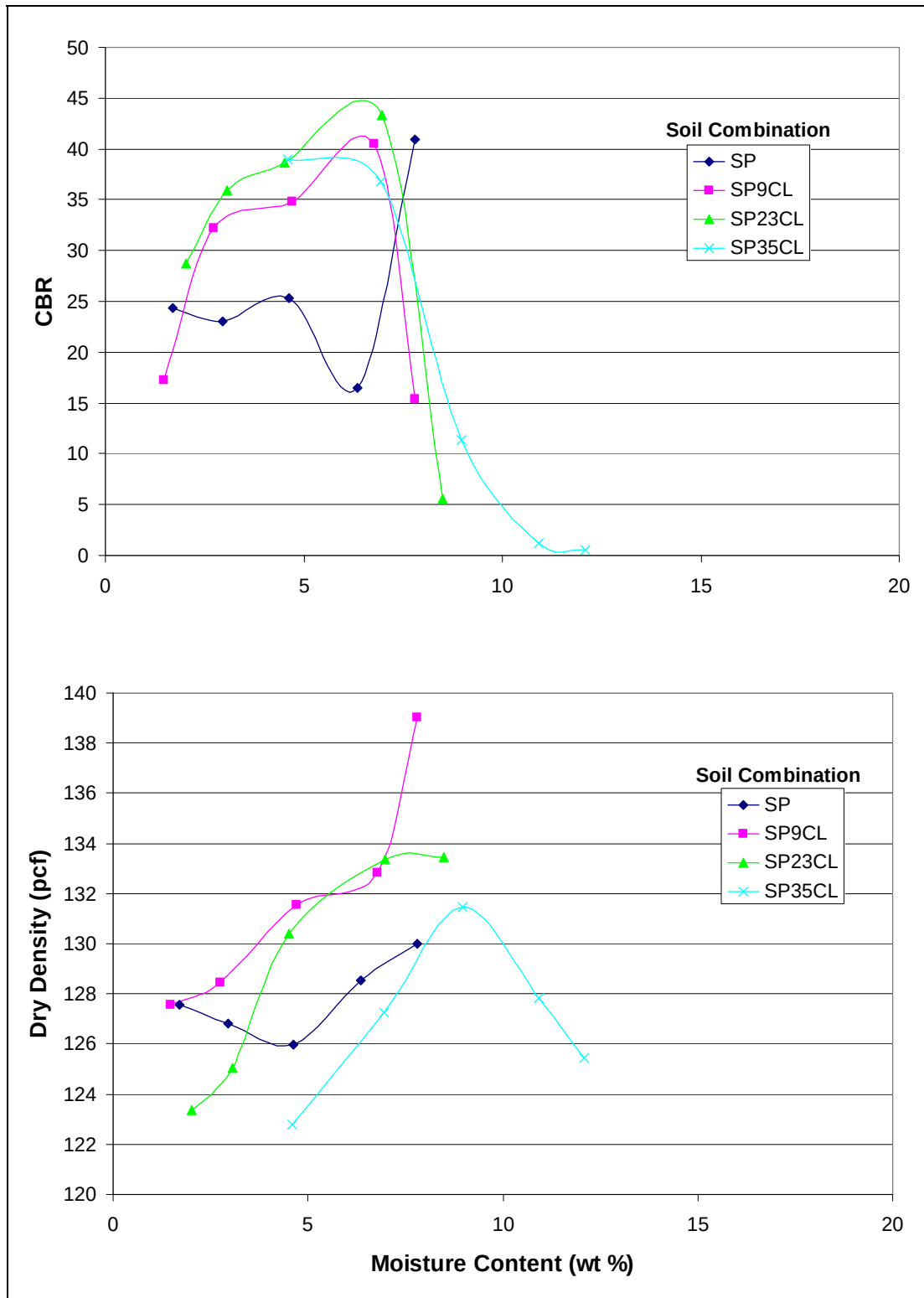
B5 CBR Variation with Percentage of Fines

Figure B-33. CBR variation with percentage of fines for SP soil combined with CL soil, 13,795 ft-lb/ft³ compaction effort.

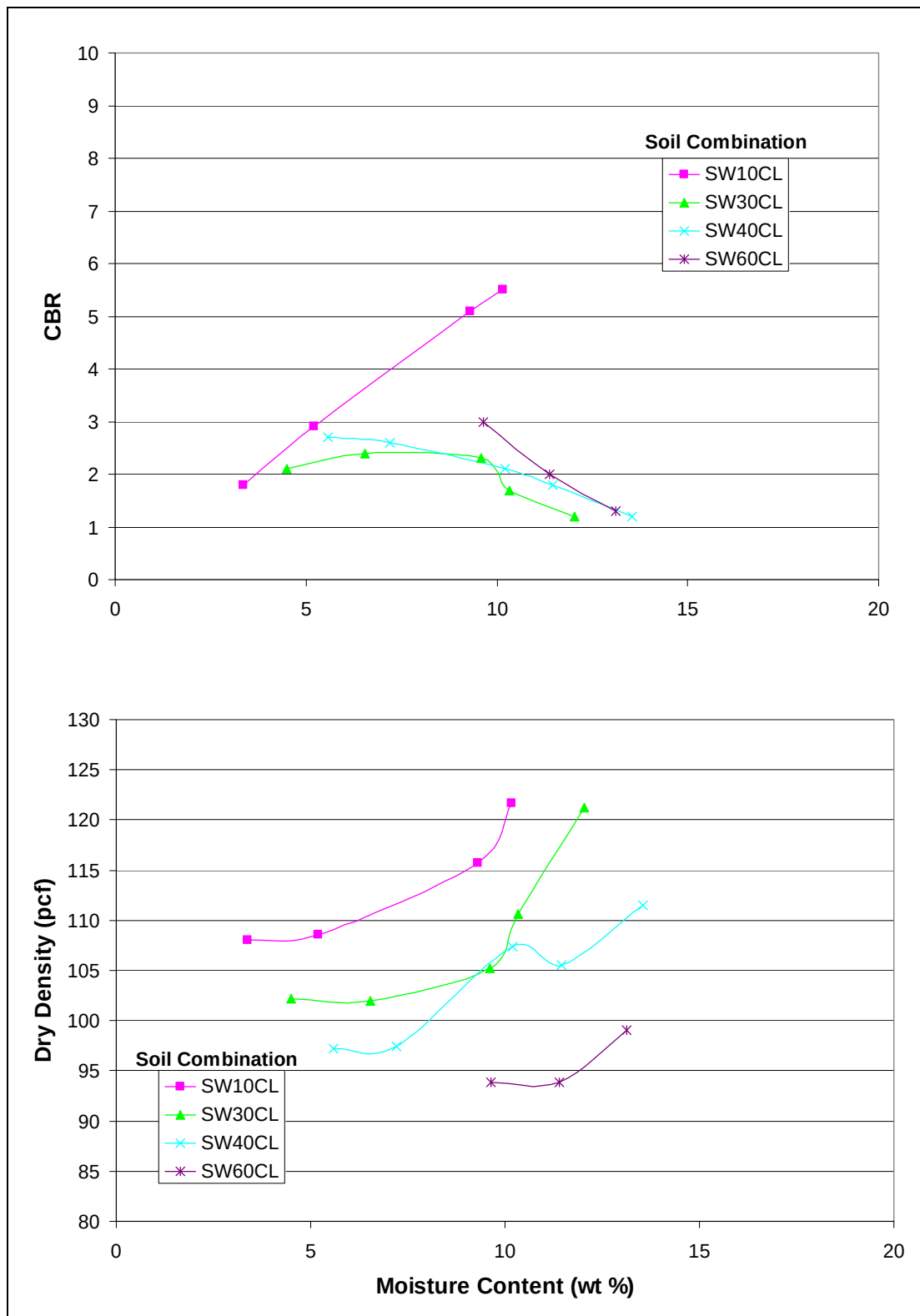


Figure B-34. CBR variation with percentage of fines for SW soil combined with CL soil, 935 ft-lb/ft³ compaction effort.

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13. SUPPLEMENTARY NOTES					
14. ABSTRACT Laboratory CBR (California bearing ratio) tests were performed on soils obtained from Opportune Landing Sites (OLS) in California, Texas, and Indiana. Initial CBR samples were prepared using standard American Society for Testing and Materials (ASTM) methods (i.e., compaction effort). Standard laboratory methods rarely reproduce in-situ density, moisture, and CBR values and therefore do not accurately represent the complete range of these values measured in the field. Because the OLS program focuses on natural unprepared sites for use as landing zones, a repeatable method of reproducing in-situ strength CBR values in the laboratory was necessary. By reducing the compaction effort on the laboratory samples, density and moisture regimes found in field conditions were more closely matched. Various compaction techniques were used to prepare consistent, low-density samples for CBR measurements. A companion study was performed for a detailed analysis on the effect of fine-grained soil particles on CBR values. A well-graded (SW) and poorly graded (SP) sand were used as the base material. A clay (CL) and silt (CL-CH) were added to the sand in varying proportions. CBR samples were prepared with these blended soils using both standard and low-density compaction methods.					
15. SUBJECT TERMS California bearing ratio, CBR, Compaction, Fine-grained soils, Low-density compaction, Soil moisture curves					
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CEERD-RZA

29 July 2015

MEMORANDUM FOR DTIC-OQ, 8725 John J. Kingman Road, Fort Belvoir, VA 22060

SUBJECT: Distribution Statement Change

1. Please change the distribution limitation statement of the attached report, ERDC/CRREL TR-08-9.

a. The DTIC AD number of this is ADB340031, *Opportune Landing Site CBR and Low-Density Laboratory Database*, from May 2008.

b. The new distribution statement should be "Approved for public release; distribution is unlimited."

2. Though determined at the time of the original publication that the report should have unlimited distribution, the wrong statement was attached to the report submitted to DTIC. Therefore, the unlimited distribution statement retains the May 2008 date.

Encl

1. ERDC/CRREL TR-08-9

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DR. ROBERT E. DAVIS
Director, Cold Regions Research and
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