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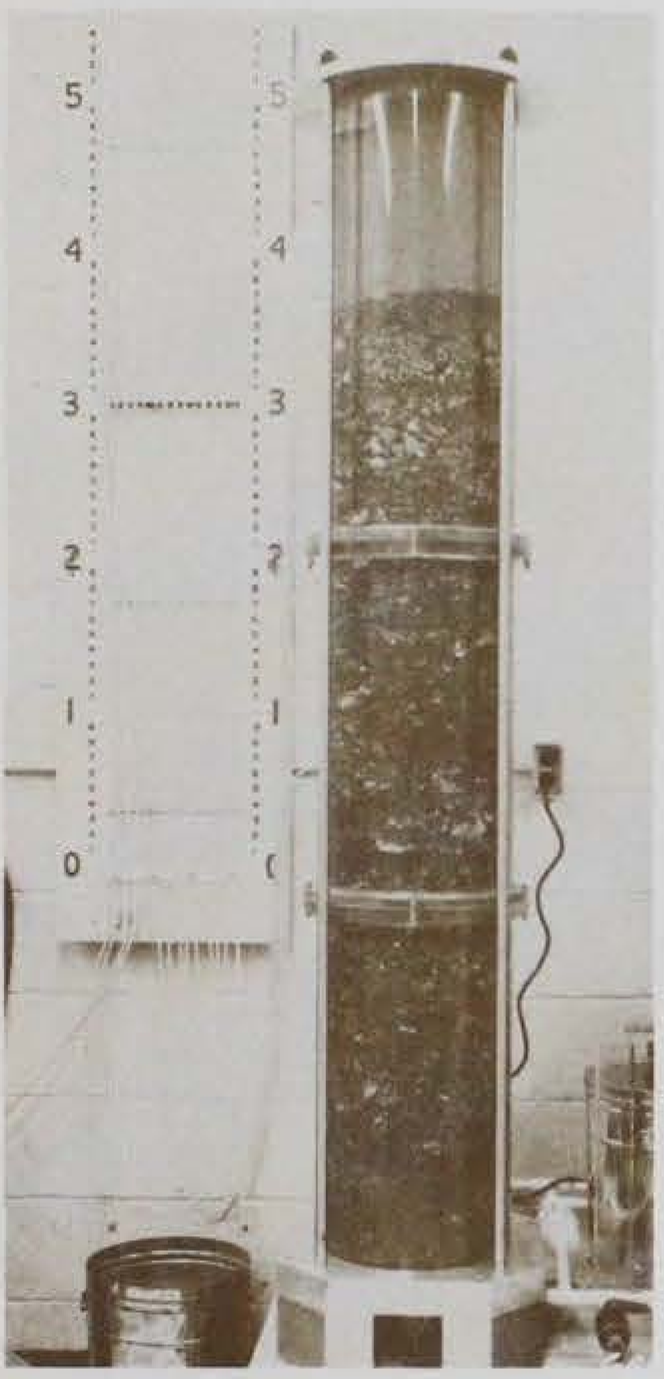

GEOTECHNICAL LABORATORY

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EVALUATION OF REVISED MANUAL COMPACTION RAMMERS AND LABORATORY COMPACTION PROCEDURES

by

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The U. S. Army Corps of Engineers currently specifies sliding weight-type rammers for laboratory compaction tests rather than sleeve-type rammers as required by the American Society for Testing and Materials (ASTM), the American Association of State Highway and Transportation Officials (AASHTO), and other organizations. This study compares 10-lb sliding weight rammers with the 10-lb ASTM sleeve rammer and compares newly designed 5.5-lb and 10-lb sliding weight rammers with low mass spring-loaded feet with the corresponding

(Continued)

20. ABSTRACT (Continued)

ASTM rammers. Five soils were used, ranging from a nonplastic silty sand to a fat clay.

The effects of (a) rate of operation of the rammers, (b) air-drying and curing the soil prior to compaction results, (c) use of a sector-shaped foot on compaction and California bearing ratio (CBR) results were investigated. Finally, various methods of calibrating mechanical compactors were investigated. Conclusions were: (a) the 10-lb sliding weight rammers currently used by the Corps of Engineers gave maximum dry densities as much as 3.0 pcf lower, and optimum water contents as much as 1.7 percent higher than the ASTM rammer; (b) the new sliding weight rammers (both 5.5-lb and 10-lb) produced maximum dry densities less than 1 pcf lower and optimum water contents less than 1 percent higher than those produced by the ASTM rammers; (c) dry density increases with increasing rate-of-blow application for both sleeve- and sliding weight-type rammers, but the magnitude of this increase varies from operator to operator; (d) there were significant effects due to air drying a fat clay prior to compaction, even when a curing period was allowed; (e) using a mechanical rammer with a sector-shaped foot to compact soil in the 6-in. mold produced the same overall compaction results but CBR values as much as 44 percent lower at optimum water content than the CBR values produced by a manual sleeve rammer; and (f) calibration of mechanical rammers by compacting soil and by deforming lead test cylinders gave good results. Guidance is given for determining the number of trials required to obtain reliable results when using lead cylinders.

PREFACE

The study reported herein was authorized by the Office, Chief of Engineers, U. S. Army, under Civil Works Investigational Study, Work Unit 31620, "Construction Problems in Placement and Control of Embankment Dams."

The study was conducted from October 1978 through December 1982 under the supervision of Mr. G. P. Hale, Chief, Soils Research Facility, and under the general supervision of Mr. C. L. McAnear, Chief, Soil Mechanics Division; Mr. J. P. Sale (Retired), former Chief, Geotechnical Laboratory (GL); and Dr. W. F. Marcuson III, Chief, GL. Persons actively engaged in the testing program were Messrs. R. C. Horz, L. R. Coffing, Jr., P. S. McCaffrey, G. T. Easley, and T. V. McEwen. Mr. Horz directed the research and prepared the report.

COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE, were Commanders and Directors of the WES during the conduct of this study. Mr. Fred R. Brown was the Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report may be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6894.757	pascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square inches	6.4516	square centimetres

EVALUATION OF REVISED MANUAL COMPACTION RAMMERS AND LABORATORY COMPACTION PROCEDURES

PART I: INTRODUCTION

Laboratory Compaction Within the Corps of Engineers

1. In the 1930's the U. S. Army Corps of Engineers began using the principles of soil compaction developed by Ralph R. Proctor in the design and construction of earth dams (Proctor 1933). Then in the early 1940's these same ideas were adapted to the construction of military airfields through research at the U. S. Army Engineer Waterways Experiment Station (WES). Proctor's original laboratory compaction method consisted of compacting soil in a 4-in.-diam,* 1/27.5 cu ft mold, using a 5.5-lb metal rod having a 2-in.-diam striking face at one end and a smaller diameter solid shaft over the rest of its length. The rammer was used to compact soil in the mold with 25 firm blows on each of three layers. The blows were to be applied from a height of 12 in. An early photograph shows a technician gaging the height from which the blows were to be applied by means of a measuring stick (Woods 1937). Mr. W. G. Shockley, WES, states that Proctor originally intended to have the rammer thrown slightly by the technician in applying the blows.** In the course of standardizing the test, however, the procedure was changed to allow the rammer to free-fall from 12 in. above the soil surface.

2. The American Association of State Highway Officials (AASHO) now the American Association of State Highway and Transportation Officials (AASHTO) published the first method for Proctor-type compaction in 1938 as Method T 99-38. This was usually referred to as Standard AASHO or Standard Proctor compaction. The American Society for Testing and Materials (ASTM) published a similar procedure in 1942 as Method D 698-42T. These methods changed Proctor's mold height to arrive at a volume of 1/30 cu ft, and required that the rammer be equipped with a suitable arrangement to control the specified drop from a height 12 in. above each firmly compacted layer.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

** Shockley, W. G. 1979. "Recollections on the Development of Compaction Hammers," unpublished Memorandum for Record, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

The method most widely adopted for controlling the height of drop was to use a metal tube or sleeve to enclose the falling weight. One early example of this type of rammer consisted of a tube open at both ends with a small-diameter wire brazed across the top of the tube to regulate the height to which the drop weight was raised (Department of the Interior, Bureau of Reclamation 1951). Problems associated with this method were soil collecting in the tube or on the drop weight and restricting the free-fall of the drop weight, air being compressed under the drop weight and slowing its fall, and the guide sleeve preventing compaction of the soil adjacent to the side of the mold. A photograph in an early War Department Technical Bulletin shows that vent holes were drilled in the sides of some sleeve-type rammers to prevent air pressure buildup (War Department, U. S. Army 1945). Australian road engineer, A. H. Gawith, attempted to solve the problems of the sleeve-type rammer by using three parallel steel rods to guide the drop weight instead of a tube (Gawith 1948). His design was apparently not used in this country. It was not until the 1964 revision of ASTM Method D 698 that a rammer having a guide sleeve and vent holes was specified.

3. Another design, used by the State Highway Commission of Kansas in the late 1930's, was the sliding weight-type rammer. It differed from the sleeve-type rammer in that the drop weight, instead of falling through a guide sleeve and impacting the soil directly, slid down a rod and struck a foot which in turn compacted the soil. This rammer was calibrated to deliver a blow equivalent to a Proctor-type rammer of 5.5 lb falling 18 in. (Hamilton et al. 1938). The foot of this rammer was solid steel and aluminum, with the shaft threaded into foot.*

4. Shockley, in recollecting the development of compaction procedures within the CE, states:**

> In the early 1940's, with our country in the throes of World War II, there was a tremendous push to design and build airfields to withstand the heavy loads of bomber aircraft. Design procedures currently in use for pavements were for streets and highways, and these were

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* Horz, Raymond C. 1982. "Recollection of State Highway Commission of Kansas Sliding Weight Compaction Rammers," unpublished Memorandum for Record, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

** Shockley, W. G. 1979. "Recollections on the Development of Compaction Hammers," unpublished Memorandum for Record, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

> inadequate for airfield loadings. It became necessary to compact subgrade and base course soils in the field to much higher densities than had been required for road and street construction. The Proctor compaction test could not achieve these higher densities in the laboratory, so efforts were started to modify the compaction test to meet these new requirements. The result was the 'modified AASHO' compaction test which is referred to as early as 1942. [See, for example, Middlebrooks and Bertram (1942).] In this test the hammer weight was increased from 5.5 to 10 lb, the height of drop from 12 to 18 in., and the number of soil layers from 3 to 5; the mold size and number of blows per layer remained the same.
>
> Parallel with the compaction test revision was the development of the CBR (California bearing ratio) test for the design of subgrades and base courses for flexible pavements. The CBR laboratory test required the compaction of soil specimens in 6-in.-diam molds at the modified AASHO compaction effort. This required 55 blows on each of five layers using the 10-lb hammer with the 18-in. drop.

5. The earliest drawings of the CBR apparatus showed a mold in which the specimens were trimmed to a 5-in. height, but this was changed before the start of the major WES investigation of the CBR test in 1942 and subsequent tests have been performed in a 4.5-in.-high mold (U. S. Army Engineer Waterways Experiment Station 1945). It had by then already been accepted that maintaining the amount of compactive effort (work applied per unit volume of soil) was the most important factor in determining the compacted density of a soil, and the 55 blows per layer in the CBR mold provided the same amount of compactive energy per unit volume of soil as 25 blows in the 4-in.-diam, 1/30 cu ft AASHO mold.

6. Shockley writes:

> At WES the effort to reduce labor in the preparation of CBR specimens resulted in the development of the sliding-weight hammer by R. M. (Bob) German. The hammer was made by Willie Rodgers in the Machine Shop. Early versions of the hammer had two problems. One was separation of the foot from the handle by metal fatigue. This was solved by J. L. McRae and Rodgers by inserting a spring in the foot, allowing the foot to move independently of the guide rod and handle.

> The other was that of the falling weight hitting the side of the mold when the foot was adjacent to the mold wall. An early fix was to braze a hollow tube onto the foot into which the weight would fall [War Department, U. S. Army 1944]. Within a year or so the problem was solved with the present design where the sliding weight has a diameter smaller than the foot in the lower portion [Department of Defense 1964]. The sliding-weight hammer appears to have been first developed about 1943 and the final design achieved by 1948.
>
> Also during this same period, WES selected the Marshall stability test for the design of asphalt paving mixtures. The test was developed by Bruce Marshall of the Mississippi Highway Department. In its earliest version, asphaltic concrete specimens were compacted in a 4-in.-diam Proctor compaction mold, using a 5.5-lb Proctor hammer. Marshall came to WES to further develop his method and in so doing, the modified AASHO hammer was adopted. A later change to the asphalt compaction hammer involved enlarging the foot to a diameter of 3-7/8 in.

7. According to Patrick S. McCaffrey, a technician at WES during the period, a 5.5-lb, 12-in. drop version of the sliding-weight rammer was being used for standard AASHO compaction tests as early as 1945. Photographs of both 5.5-lb and a 10-lb sliding-weight type rammers were shown in the soils testing manual for the Lower Mississippi Valley Division, Corps of Engineers (CE) in 1951 (U. S. Army Corps of Engineers 1951). A detailed drawing of the 10-lb sliding-weight type rammer, essentially identical to the current design, appeared in the Engineer Manual for Military Construction in 1951 (Department of the Army, Office, Chief of Engineers 1951). The rammer is described as being for "soil and asphalt tests."

8. While the sliding-weight rammer was used by some CE laboratories in the 1950's and 1960's, many used sleeve-type or mechanical rammers. From unpublished information on testing procedures collected at the time of a cooperative testing program among CE laboratories, three of the ten laboratories reporting used the sliding-weight type rammer, three used a sleeve-type rammer, and four used mechanical rammers. It was not until 1965 when the first edition of Laboratory Soils Testing was published that the sliding-weight rammer was specified for laboratory compaction on Civil Works projects (Department of the Army, Office, Chief of Engineers 1965).

9. In the latest development to date, the 1970 edition of Laboratory Soils Testing specifies a 5.5-lb sliding-weight rammer in which the spring is removed and the foot attached rigidly to the guide rod (Department of the Army, Office, Chief of Engineers 1970). This change was made in response to complaints of high manufacturing cost for the rammers with spring-cushioned foot. Specific requirements for the 10-lb rammer were not made in this Engineer Manual, but the original problem of foot breakage with the 10-lb rammer has necessitated the continued use of the spring-cushioned 10-lb rammer in most laboratories.

10. In an alternate line of development, AASHO standardized the higher compactive effort of the CE "modified AASHO" test in 1957 as test method T 180-57. The ASTM followed in 1958 with Method D 1557-58T. Both of these standards, as well as the ASSHO and ASTM revisions of the Standard Proctor tests made at that time, introduced the use of a 6-in.-diam mold as an alternate to the 4-in. mold. When this was done, the height of the 6-in. mold was kept the same as the 4.59-in. height originally specified for the 4-in., 1/30 cu ft mold. To provide the same compactive effort as used in the 4-in. mold, 56 blows per layer were required. Thus the number of blows per layer in the AASHO and the ASTM standards was 56 blows per layer versus 55 specified by the CE for compaction in the 4.5-in.-high mold.

11. Over the years, the 10-lb rammer and CBR mold have continued to be used for both compaction and CBR testing in military construction manuals. But while the sliding-weight rammer has been specified in some CE specifications for laboratory compaction, others do not specify the type of rammer to be used, merely stating that the rammer shall have a suitable guide for controlling the height of drop. In fact, the sleeve-type rammer was included in test sets for U. S. Army Engineer troops at least as early as 1945, and has continued to be shown in Army Technical Manual 5-530, "Materials Testing," to the present (War Department, U. S. Army 1945, Departments of the Army and Air Force 1966). This manual also allows the use of the 6-in. ASTM mold and the CBR mold interchangeably.

12. When ASTM published the CBR test as Method D 1883-61T, the size of the molded specimen was 4.59 in. high to correspond to the height of specimen in ASTM compaction test methods. It was also specified that specimens compacted to lower densities be compacted using the ASTM standard effort compaction using a 5.5-lb rammer. The CE method for compaction and

CBR tests, as currently found in Military Standard MIL-STD 621A, varies the compactive effort for molded specimens by varying the number of blows per layer while keeping the rammer size the same (Department of Defense 1964). The compactive efforts that have been used over the years have been either 12, 26, or 55 blows per layer, depending on the densities desired; 12 blows per layer supplies approximately the same compactive effort as that of standard AASHO or ASTM compaction. Current requirements for Civil Works construction call for use of 4- and 6-in. molds, both having a height of 4.59 in., and the use of 5.5- or 10-lb rammers, depending on whether standard or modified effort is required.

13. With regard to the development of mechanical compactors, Shockley writes:

> The physical effort of preparing specimens for the modified AASHO compaction test and the CBR test was considerably greater than that required for the old Standard Proctor test. It was only natural, therefore, that personnel in many laboratories started to develop mechanical compaction devices to reduce the physical labor of compacting a soil specimen. Many such devices were built, ranging from a simple cord attached to the hammer handled and passing over a pulley to sophisticated devices that raised the hammer, rotated the mold, dropped the hammer, counted the number of blows, and automatically shut off when a prescribed number of blows had been applied. Efforts were made in most cases to calibrate these devices so that they would duplicate the results of the hand-operated drop hammer.

14. An early report describes the construction and testing of a mechanical compactor at WES (U. S. Army Engineer Waterways Experiment Station 1950). In this report, results of the mechanical compactor were compared to hand-compaction results. In 1959 the U. S. Bureau of Reclamation reported the development of a calibration procedure for mechanical compactors designed to eliminate the need for preparing soil specimens (Holtz and Merriman 1959). This procedure was later refined and issued as a standard Bureau of Reclamation test procedure (Department of Interior, Bureau of Reclamation 1962). The procedure compares the deformation of small lead cylinders caused by the impact of the manual and mechanical rammers instead of comparing the densities of compacted soil specimens. The ASTM adopted this method of

calibrating mechanical compactors in 1964 as Method D 2168-63T.

15. It was also not until 1964 that ASTM revised their Methods D 698 and D 1557 to specifically provide for the use of a sector-shaped striking surface on mechanical compactors to permit complete coverage of the soil surface when compacting in a 6-in.-diam mold. Objections to the use of the sector-shaped foot within the Corps of Engineers have arisen because of reports that the CBR values obtained from specimens compacted with a sector-shaped foot are lower than those produced by a round foot. At present, Laboratory Soils Testing permits mechanical compactors but prohibits the use of a sector-shaped foot.

History of This Investigation

16. In 1972 it was reported that standard compaction test results from the CE Clarence Cannon Dam Project soils laboratory did not agree with results obtained at the WES on similar soil (Young 1973). Investigation of the discrepancy led to a study of manual and mechanical compaction rammers by Durham and Hale (1977). Their study concluded that:

a. The sleeve-type rammer specified by the ASTM for laboratory compaction tests (Method D 698) produced higher maximum dry densities than the CE sliding-weight type rammer.

b. The rate of applying blows with either the sleeve-type or the sliding-weight type rammer affected the results obtained.

c. More consistent results were obtained using mechanical compactors than manual rammers, even though the rates of blow application were different for the various mechanical compactors.

d. Mechanical rammers calibrated using lead test cylinders, as described in ASTM Method D 2168-66, did not produce the same maximum dry densities as a manual sleeve rammer, nor did mechanical rammers calibrated using lead cylinders produce the same maximum dry densities with one another.

The present study is intended to fulfill the recommendations made in the aforementioned study and to extend that work as described below.

Purpose of Study

17. The purposes of the present study were to:

a. Redesign the CE 5.5-lb sliding-weight rammer to minimize or, if possible, eliminate differences between this rammer and the sleeve-type rammer.

b. Compare the performance of the 10-lb sleeve-type, solid foot sliding-weight, and Military design sliding-weight rammers in modified effort compaction (4-in. mold, five layers, 25 blows per layer) and CE-12 effort compaction (6-in. mold, five layers, 12 blows per layer). If significant differences appear between the 10-lb sleeve- and sliding-weight type rammers, design a 10-lb sliding-weight rammer to minimize or eliminate the difference.

c. Investigate and eliminate possible variables in current CE compaction test procedures, with particular emphasis on developing specifications for rate-of-blow application.

d. Establish practical procedures for the calibration and use of mechanically operated rammers.

Literature Review

Comparisons of manual and mechanical rammers

18. The earliest data obtainable comparing sleeve- and sliding-weight type rammers were in a WES report in which 10-lb sleeve- and sliding-weight type rammers were compared in modified effort compaction tests on CH, CL, and GC soils (U. S. Army Engineer Waterways Experiment Station 1959). About 0.6 pcf was the maximum difference in maximum dry densities with optimum water contents differing by up to 0.4 percent. The sleeve-type rammer showed lower dry densities on the CH and CL soils and higher dry densities on the GC soil. This report also presented data collected from 11 CE offices in which comparisons were made between the results of hand compaction and mechanical compaction. While the type of manual rammer and compactive effort were not specified, the 47 comparisons showed that the optimum water contents agreed within 2 percentage points and the maximum dry densities agreed within 3 pcf.

19. In 1966 Turnbull* reported a series of compaction tests in which a 5.5-lb sliding-weight type rammer with spring-cushioned foot was compared to the same rammer with a solid metal spacer substituted for the spring. The total weight of the rammer with metal spacer was 31 g (0.17 lb) heavier than the rammer with spring. The tests were performed on ML, CL, and CH soils

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* Turnbull, W. J. 1966. "Comparison Study, 5-1/2 lb Falling-Weight Compaction Hammers," Letter to Chief of Engineers, U. S. Army, from Soil Mechanics Division, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

used in a previous study (Strohm 1966). In these tests, the maximum dry densities were 1.0 pcf less for the solid foot rammer on CH soil, and the optimum water content was 1.2 percent higher. The solid foot rammer obtained slightly higher results on the CL soil and results on ML soil were virtually identical.

20. The WES reported a limited amount of test data comparing the results of compaction in a 6-in.-diam mold at various compactive efforts using a mechanical compactor with sector-shaped foot and a 10-lb manual sliding-weight rammer (U. S. Army Engineer Waterways Experiment Station 1950). The drop weight, drop height, and number of blows per layer differed from that of the manual rammer, but compared on a compactive effort basis, the mechanical rammer produced results that varied from 2-1/2 pcf more to 3 pcf less than the manual rammer.

21. Durham and Hale, in the report which provided the impetus for this study, compared 5.5-lb sleeve, solid foot sliding-weight and mechanical rammers and found that the sliding-weight rammer gave results which were consistently lower than the results achieved with the sleeve rammer (Durham and Hale 1977). It was shown in this report that with the same operator, maximum dry densities obtained by the solid foot sliding-weight rammer were as much as 6 pcf less than those obtained using a sleeve-type rammer. This study also compared three models of mechanical rammers with the sleeve and sliding-weight rammers and found that while the mechanical rammers differed from each other, all produced maximum dry densities that were within 1.5 pcf of the results obtained with the sleeve-type rammer after being calibrated by the lead cylinder method described in ASTM Method D 2168-66, "Standard Method for Calibration of Mechanical Laboratory Soil Compactors." One (unexplained) observation made in the study was that each mechanical rammer consistently produced soil densities that fell in the same relative rank with respect to the other mechanical rammers (but not necessarily the sleeve rammer), even though each rammer had been calibrated to produce the same results using Method D 2168. This study also demonstrated that rate-of-blow application could affect dry densities obtained with either of the manual rammers, but the sliding-weight type rammer results were much more subject to rate-of-blow application. Increases of up to 4.6 pcf were found for the sliding-weight rammer and 1.6 pcf for the sleeve rammer at the faster rates.

22. In the Durham and Hale study most of the testing was performed by one operator. However, a second operator performed some tests for comparison and this operator produced dry densities that were lower than the primary operator even when the primary operator performed the tests at a slow rate-of-blow application.

23. In 1975 the South Atlantic Division Laboratory reported results of a limited study on soil from the West Point Dam project in which it was found that a 5.5-lb sliding-weight rammer having a total rammer weight 2.2 lb greater than was typical for such rammers, produced results on an MH soil that were 2.5 pcf less than those produced by a more typical rammer.* This study also found that the densities produced when compacting at a 75-100 blows/min rate averaged 1.2 pcf greater than those produced when compacting at a 37-50 blow/min rate.

24. Dawson reported comparison tests between a Rainhart brand mechanical compactor and manual sleeve rammers, both 5.5 lb and 10 lb (Dawson 1959). The average maximum dry density for the four soils tested and for both standard and modified compactive effort was 1.4 pcf higher for the manual sleeve rammers than for the Rainhart mechanical rammer. The tests were performed in a 4-in. compaction mold. When the mechanical rammer using a sector-shaped foot was compared with the manual rammers in a 6-in. mold, the results were essentially the same (0.3 pcf higher for the manual rammer). In tests performed to evaluate the uniformity of compacted specimens, it was reported that density tended to decrease from bottom to top of specimen regardless of the foot used. However, when comparing the density at the center of specimens to the density near the perimeter, the density near the center averaged about 1 pcf higher than the outer portion with the round foot. Specimens compacted with the sector-shaped foot were uniform from the center outward.

25. The California Department of Transportation compared the performance of a mechanical rammer built to California Department of Transportation specifications to a 10-lb ASTM sleeve-type rammer in modified effort compaction tests (ASTM Method D 1557) (Hatano et al. 1976). When eight specimens

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* U. S. Army Engineer Division Laboratory, South Atlantic. 1975. "Comparison of Project and SAD Laboratory Standard Compaction Test Results, West Point Project East Earth Embankment," Internal Report (draft), Marietta, Ga.

at optimum water content were compacted using each rammer, the coefficient of variation computed and then averaged for all of the 17 soils used in the testing program, the manual rammer showed less variance than the mechanical rammer (0.46 versus 0.61). To evaluate the effect of tilting or soil accumulation in the sleeve on the performance of the manual rammer, several tests were conducted with the rammer tilted 5 and 10 deg from vertical and with soil accumulation on the inside of the sleeve. The rammer was used to deform lead slugs and the deformations were compared with the deformations of a clean rammer held vertically. The authors concluded that sufficient decrease in compactive effort resulted from tilting and soil accumulation such that under the less controlled conditions experienced in most laboratories, the mechanical rammer would give more consistent results. The authors further concluded that a calibration method such as the use of lead slugs was unnecessary and, for the mechanical compactor of the type specified, only the weight of the falling mass and the height of drop needed to be checked. It must be pointed out, however, that the specifications for a mechanical rammer proposed by the authors require that the performance of the rammer be verified before acceptance by being able to make reproducible impacts on an electronic load cell-chart recorder setup.

26. In a discussion of Dawson's paper, Holtz and Merriman describe a method of calibrating mechanical rammers by having the rammer indent a pat of lead with a steel ball (Holtz and Merriman 1959). The data presented by Holtz and Merriman showed that a mechanical rammer of the same type used by Dawson could produce results 1.3 pcf less (on one data point 6.2 pcf less) than that produced by hand compaction when using the Bureau of Reclamation compaction requirement of 5.5-lb rammer with 18-in. drop in a 1/20 cu ft mold. The authors stated that the mechanical rammer results were much more reproducible than hand rammer results when several identical tests were made on the same soil.

27. The method described by Holtz and Merriman was later revised to use commercially available lead cylinders (Department of the Interior, Bureau of Reclamation 1962).

Effect of soil processing on compaction test results

28. Several investigations have demonstrated the effects that air- or oven-drying of soil prior to testing have on compaction test results

(Ray and Chapman 1954, Johnson and Sallberg 1962). From such investigations, it has generally been accepted that when a soil has been dried prior to compaction, a curing period is necessary after mixing water with the soil and before compacting. Maximum dry densities obtained when soil has not been allowed to cure are usually higher than for soils allowed to cure before testing, particularly for soils of higher plasticity.

29. The current CE practice, as stated in Appendix VI of Laboratory Soils Testing, is to air-dry all soils, then rewet the soils and allow them to cure at least 16 hr before testing (Department of the Army, Office, Chief of Engineers 1970). This contrasts to common field laboratory practice where soil is processed at natural water content and then air-dried or wetted as necessary to attain the range of water contents needed for a compaction test. The South Atlantic Division Laboratory, CE, reported that the differences in results between tests performed at one of their field laboratories and the Division laboratory were in part due to this difference in soil preparation procedure.* The soils being tested in this investigation were classified as MH and were known to contain halloysite clay mineral which in certain forms is irreversibly affected by drying. Several other investigations have demonstrated the effect of air-drying tropical soils or soils containing halloysite on the results of compaction tests (Frost 1967, Brand and Hongsnoi 1969). It has also been shown that air-drying and then rewetting a crushed shale having a particle size range of sand changed its compacted dry density by about 6 pcf from that of the nonair-dried material (Bailey 1976).

Outline of Testing Program

30. The testing program consisted of the following:

a. Evaluate 5.5-lb rammers.
   (1) Test trial designs for a new 5.5-lb sliding-weight rammer with low mass, spring-loaded foot on CH soil using standard effort. Finalize design.
   (2) Develop standard effort compaction curves on five soils using sleeve and new sliding-weight rammers. Test a second sleeve rammer with slots cut in sleeve to reduce binding on the CH, SM, and SC soils.

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* U. S. Army Engineer Division Laboratory, South Atlantic. 1975. "Comparison of Project and SAD Laboratory Standard Compaction Test Results, West Point Project East Earth Embankment," Internal Report (draft), Marietta, Ga.

(3) Develop 15-blow effort compaction curves on five soils using sleeve and new sliding-weight rammers.

b. Evaluate 10-lb rammers.

(1) Evaluate performance of present 10-lb rammers.

(a) Develop modified effort compaction curves on five soils using 10-lb sleeve, Military specification sliding-weight, and solid foot sliding-weight type rammers.

(b) Develop CE-12 effort compaction curves on five soils using 10-lb sleeve, Military specification sliding-weight, and solid foot sliding-weight type rammers.

(2) Design 10-lb sliding-weight rammer with low mass, spring-cushioned foot along same lines as new 5.5-lb sliding-weight rammer and evaluate with respect to sleeve rammer.

(a) Develop modified effort compaction curves on five soils using new 10-lb sliding-weight rammer for comparison with 10-lb sleeve rammer.

(b) Develop CE-12 effort compaction curves on five soils using new 10-lb sliding-weight rammer for comparison with 10-lb sleeve rammer.

c. Evaluate test variables.

(1) Effect of rate-of-blow application. Compare specimens of CH soil compacted at about 3 percent dry of optimum at five or more rate-of-blow applications using:

(a) 5.5-lb sleeve and new sliding-weight rammers at standard effort with two operators.

(b) 5.5-lb solid foot rammer at standard effort using an experienced operator.

(c) 10-lb sleeve and new sliding-weight rammers at CE-12 effort and with two operators.

(2) Effect of different processing procedures. Develop standard effort compaction curves on a CH soil after preparing soil in the following ways:

(a) Completely air-dry, pulverize, rewet batches to desired water contents, process, and cure for 72 ± 6 hr.

(b) Air-dry to approximately 6 percentage points below optimum, rewet batches to desired water contents, process, and cure for 72 ± 6 hr.

(c) Separate wet soil into batches, air-dry each batch to desired water content, process, and cure for 72 ± 6 hr.

(d) Completely air-dry, pulverize, rewet batches to desired water contents, and process.

(e) Air-dry to approximately 6 percentage points below optimum, rewet batches to desired water contents, and process.

(f) Separate wet soil into batches, air-dry each batch to desired water content, and process.

(3) Effect of sector shaped foot. Produce compaction curves and determine CBR values for five soils. Compare data from:

(a) Specimens compacted in 6-in. mold at standard effort using mechanical rammer with sector foot and specimens compacted using manual rammer (circular foot).

(b) Specimens compacted in 6-in. mold at modified effort using mechanical rammer with sector foot and specimens compacted using manual rammer (circular foot).

d. Calibration methods for mechanical compactors.

(1) Perform preliminary screening of the following methods by noting ability of method to detect differences between mechanical rammer or manual rammer impacts:

(a) Measure drop weight and height of drop.

(b) Compact CH soil.

(c) Lead test cylinders (ASTM Method D 2168-80).

(d) Coil-spring type calibrator.

(e) Rubber-cylinder type calibrator.

(f) Compact crushable material (Perlite).

(g) Compact pulverized air-dried soil.

(h) Friction-type calibrator.

(i) Load cell and oscilloscope readout.

(2) Adjust rammer to match results of manual rammer on CH soil and recalibrate using methods selected from preliminary screening.

PART II: TESTING PROGRAM

Equipment

31. The compaction equipment used for this study consisted of two compaction molds, eight manual compaction rammers of various types, and one automatic compactor, described as follows:

a. Molds. Four-in.-diam and six-in.-diam straight-sided molds were used for all the compaction tests in this study. The molds used for compaction only met the requirements of ASTM Method D 698-78 and Engineer Manual EM 1110-2-1906. The CBR molds met the requirements of ASTM Method D 1883-73 and Military Standard MIL-STD 621A except that the overall length of the molds was 8 in. and the metal spacer used with the molds was 3.416 in. thick resulting in a specimen approximately 4.58 in. high. Dimensions of the molds are given in Table 1. Note that the CE-12 effort compaction tests were performed in molds which were 4.58 in. high rather than 4.50 in. high as specified in MIL-STD 621A.

b. Manual rammers. The dimensions of the various manual rammers used in this study are given in Table 2 and illustrated in Figures 1-4. The 5.5-lb and 10-lb sleeve rammers meet the requirements of ASTM Methods D 698-78 and D 1557-78, respectively. A 5.5-lb sleeve rammer in which four equally spaced slots, approximately 1 in. wide by 7 in. long, had been milled in the lower end of the sleeve was also used. The 5.5-lb and 10-lb solid foot sliding-weight rammers met the requirements of Engineer Manual EM 1110-2-1906 and the Military rammer conformed to Military Standard MIL-STD 621A. The new design sliding-weight rammers had drop weights, drop heights, and striking face diameters corresponding to the other rammers used in the study.

c. Mechanical compactor. The mechanical compactor was a Soiltest Model CN4230, shown in Figure 5. The compactor is designed so that the height of drop can be made either 12 or 18 in. However, no fine adjustment of the height of drop was possible, so the compactor was modified by reworking the lower dog guide to permit about 1 in. of adjustment in the height of drop. Prior to making the height of drop adjustable, the average height of drop was 12-5/32 in. when operated slowly by hand and 12-1/2 in. when in continuous automatic operation. In both instances, the actual height of drop varied over a range of about 5/32 in. due to the design of the rammer-raising mechanism. To comply with the ASTM requirement that there be 0.1 ± 0.03-in. clearance between the rammer and the inside surface of the mold, the hole in the lower end of the rammer shaft was slotted to make the position of the foot adjustable without changing the positioning of the shaft. This modification resulted in the round foot being slightly off-center with respect to the rammer shaft when set up for operation in the 4-in. mold. The striking face of the round foot was 1.998 in. in diameter. When set up to perform compaction in the 6-in.-diam molds, a sector-shaped foot,

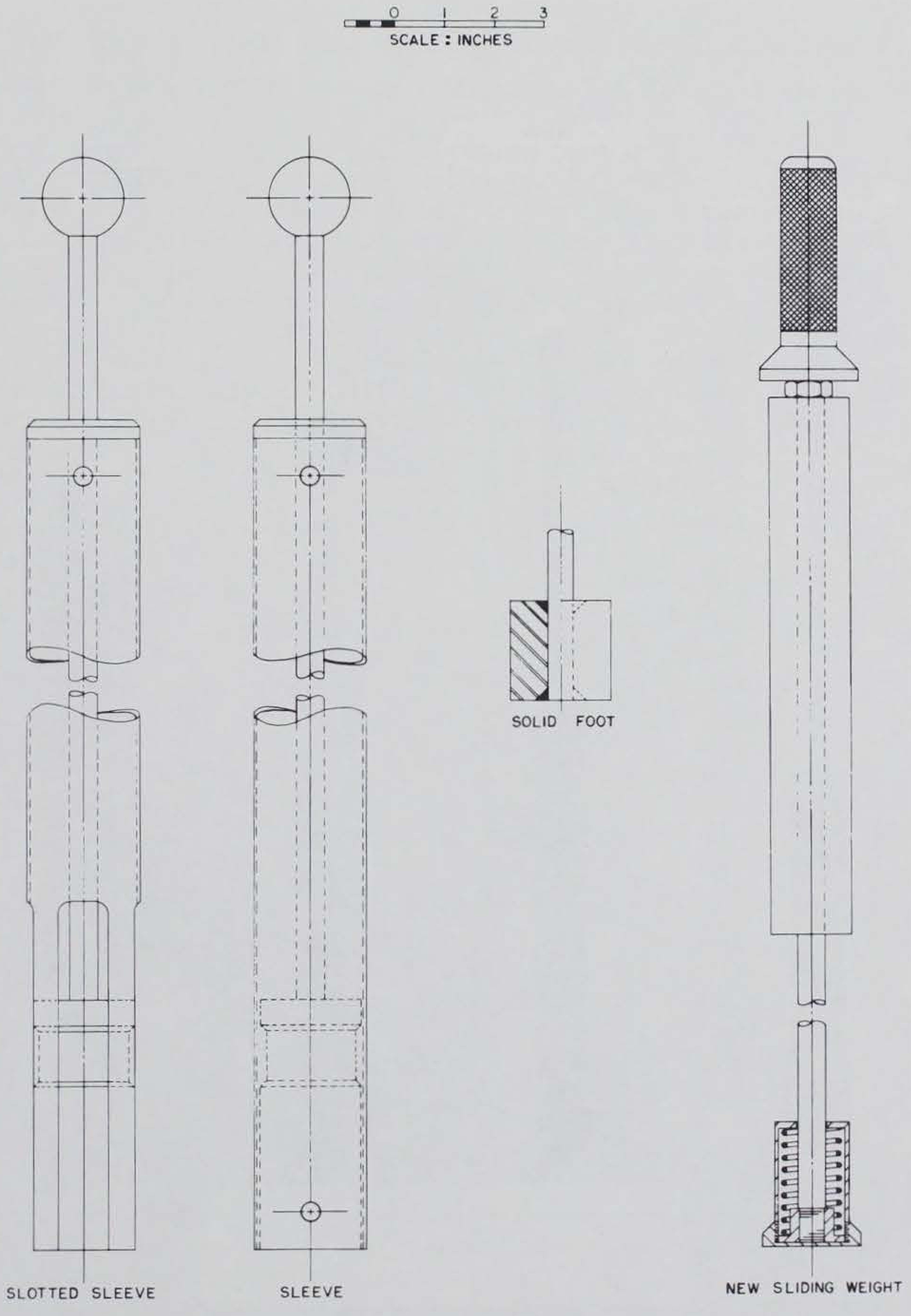


Figure 1. Construction of 5.5-lb manual compaction rammers

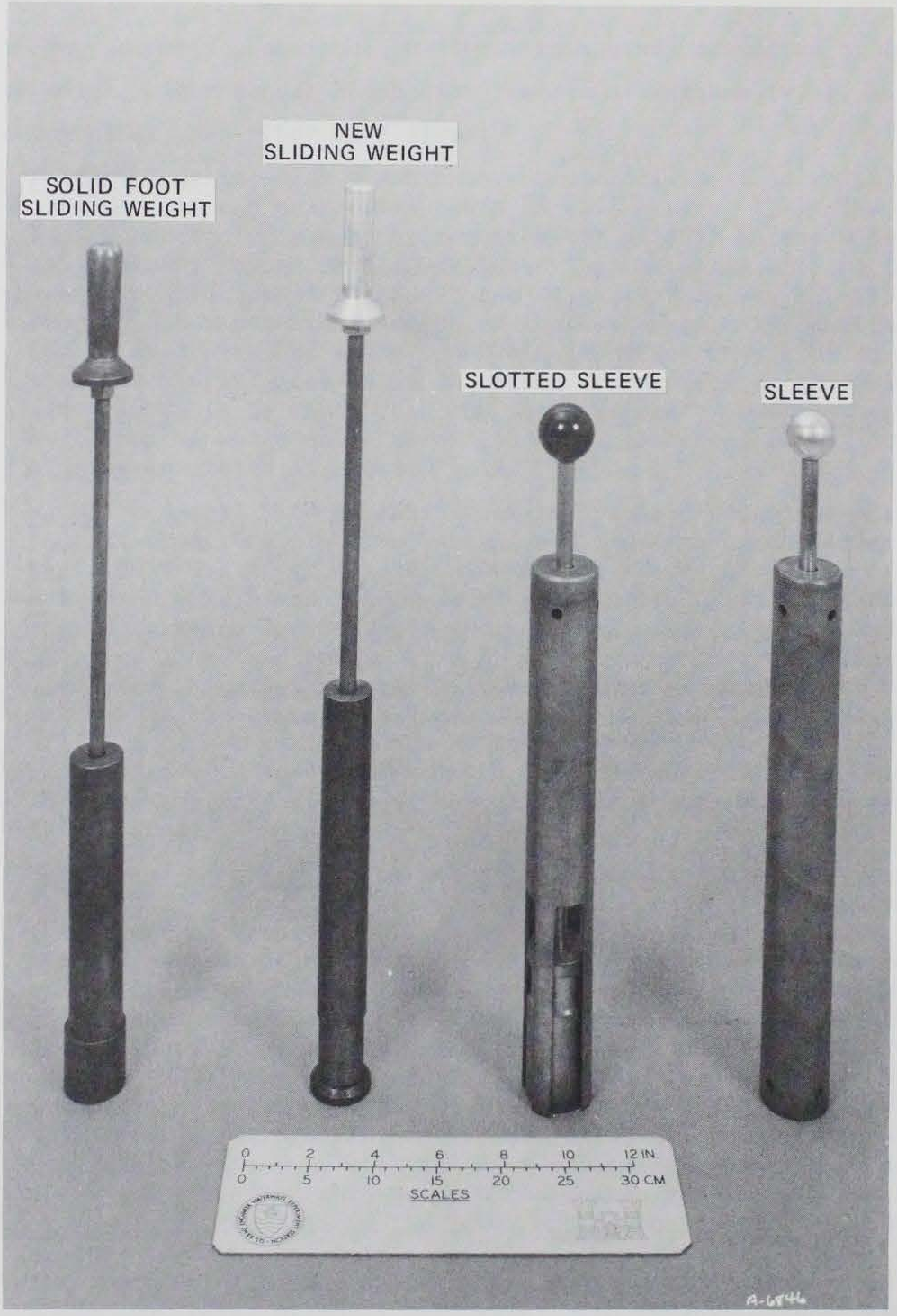


Figure 2. Manual compaction rammers, 5.5-lb

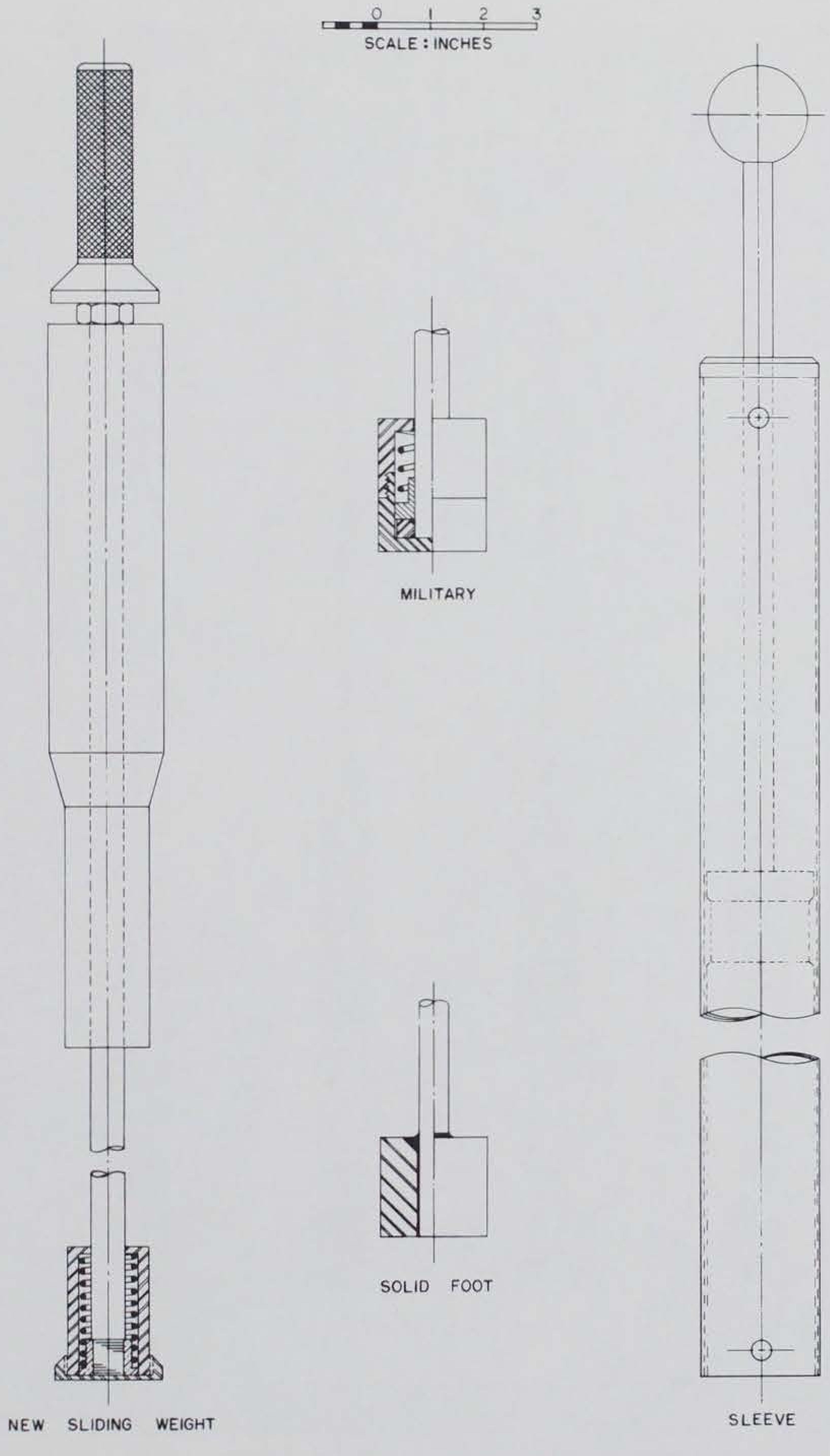


Figure 3. Construction of 10-lb compaction rammers

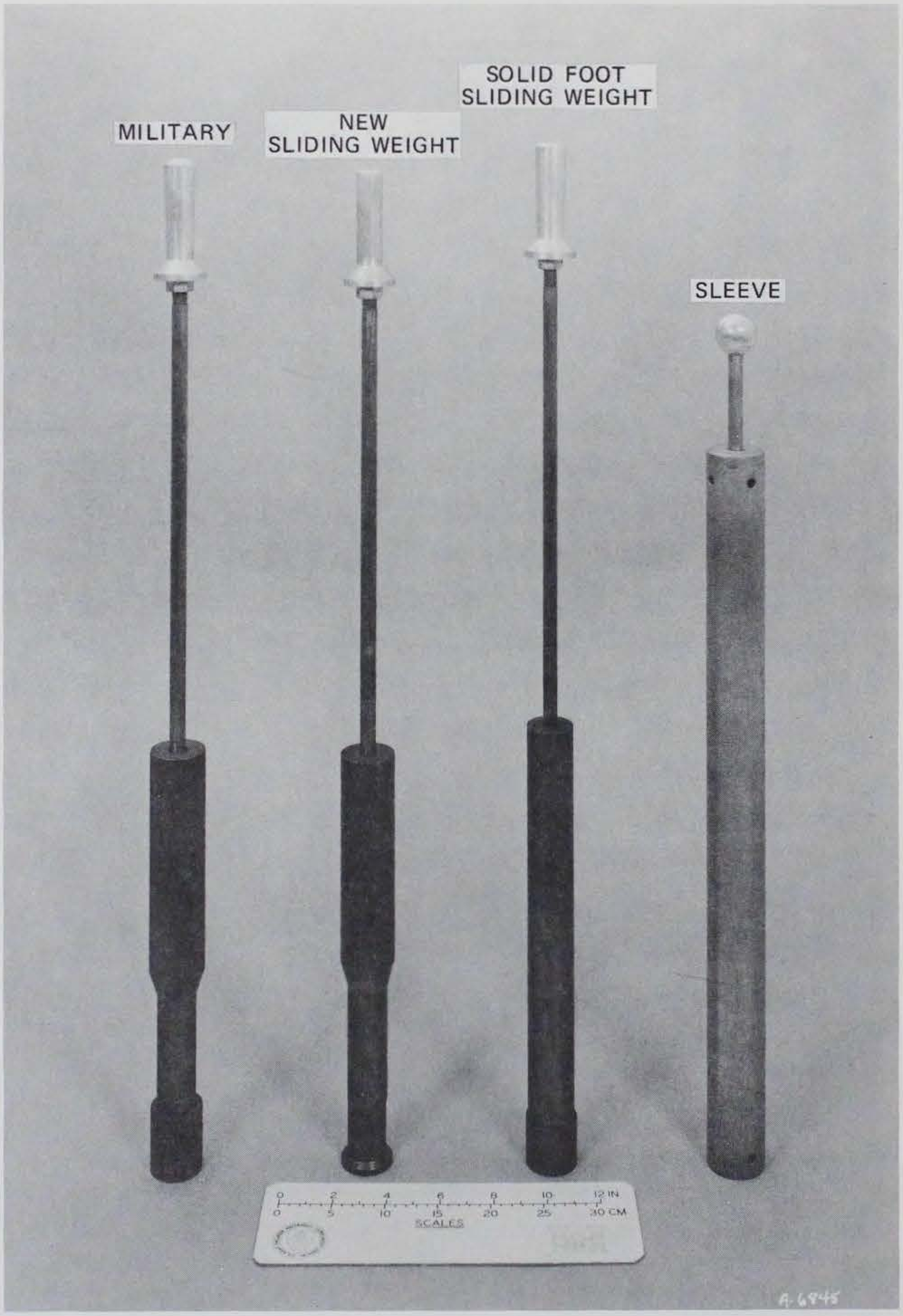


Figure 4. Manual compaction rammers, 10-lb

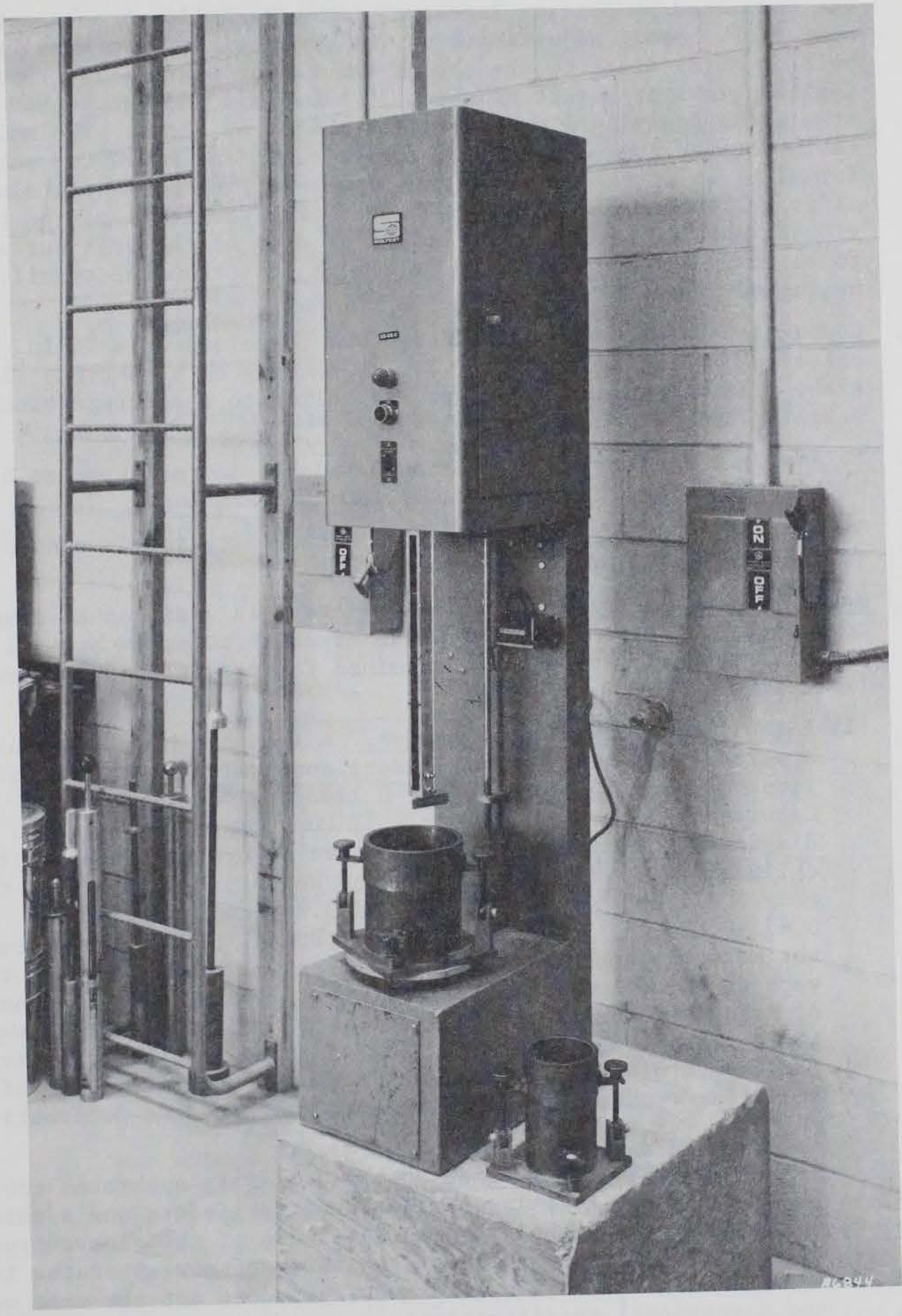


Figure 5. Mechanical compaction rammer and molds

supplied by Soiltest, Inc., was used. The bottom surface of the foot had a sector angle of 43 deg and a radius of 2.889 in. for an area equivalent to that of the circular foot. For compacting specimens using modified effort compaction, the weight of the rammer was increased by putting lead pats into the hollow drop shaft of the compactor. Small adjustments of the drop weight were made by bolting metal discs to the top of the rammer shaft. The rammer applies blows at a rate of about 30 blows/min and can be set to stop after applying a predetermined number of blows. The mold table rotates the mold between rammer blows and makes two rotations for 21 blows of the rammer. The rammer-lifting mechanism always lifts the rammer the specified height from the level of the previously applied blow so that height of drop of the soil surface to be compacted will vary and is always less than the specified height of drop.

d. Compaction bases. Hand compaction was performed on a 15-in. concrete cube weighing just over 200 lb resting on a concrete floor slab. The mechanical compactor was bolted to a concrete block weighing over 900 lb.

e. Balance. A Mettler PS 30 balance, readable and accurate to 1 g within the range of use, was used for all weighings.

f. Oven. Soil specimens were dried in a thermostatically controlled, forced-draft oven set to maintain 110 ± 5°C.

g. Mechanical compactor calibration devices. In addition to comparing compacted soil specimens as a means of calibrating mechanical compactors, several devices were examined for use in measuring rammer impacts:

    (1) ASTM lead deformation apparatus. A lead cylinder deformation apparatus and lead test cylinders conforming to the specifications of ASTM Standard Method D 2168-80, "Calibration of Laboratory Mechanical-Rammer Soil Compactors," were used. A diagram of the apparatus is shown in Figure 6. The lead test cylinders were manufactured by the Hornady Manufacturing Company. All cylinders used weighed 9.36-9.40 g and were 0.675-0.680 in. in length. A few percent of the cylinders did not meet the aforementioned length or weight limits, and these were either trimmed to comply or were discarded. The diameters of a few percent of the cylinders were measured and all were found to be 0.309-0.311 in. For the actual deformation trials, the length of each cylinder was measured with calipers before and after impact and the difference taken as the deformation value.

    (2) Simplified lead deformation apparatus. This apparatus consisted of an anvil for locating the lead test cylinders and a guide sleeve pedestal to hold the guide sleeve of the sleeve-type rammer at the proper height. A diagram of the apparatus is shown in Figure 7. The lead test cylinders met the same weight and dimensional specifications as those used in the ASTM apparatus.

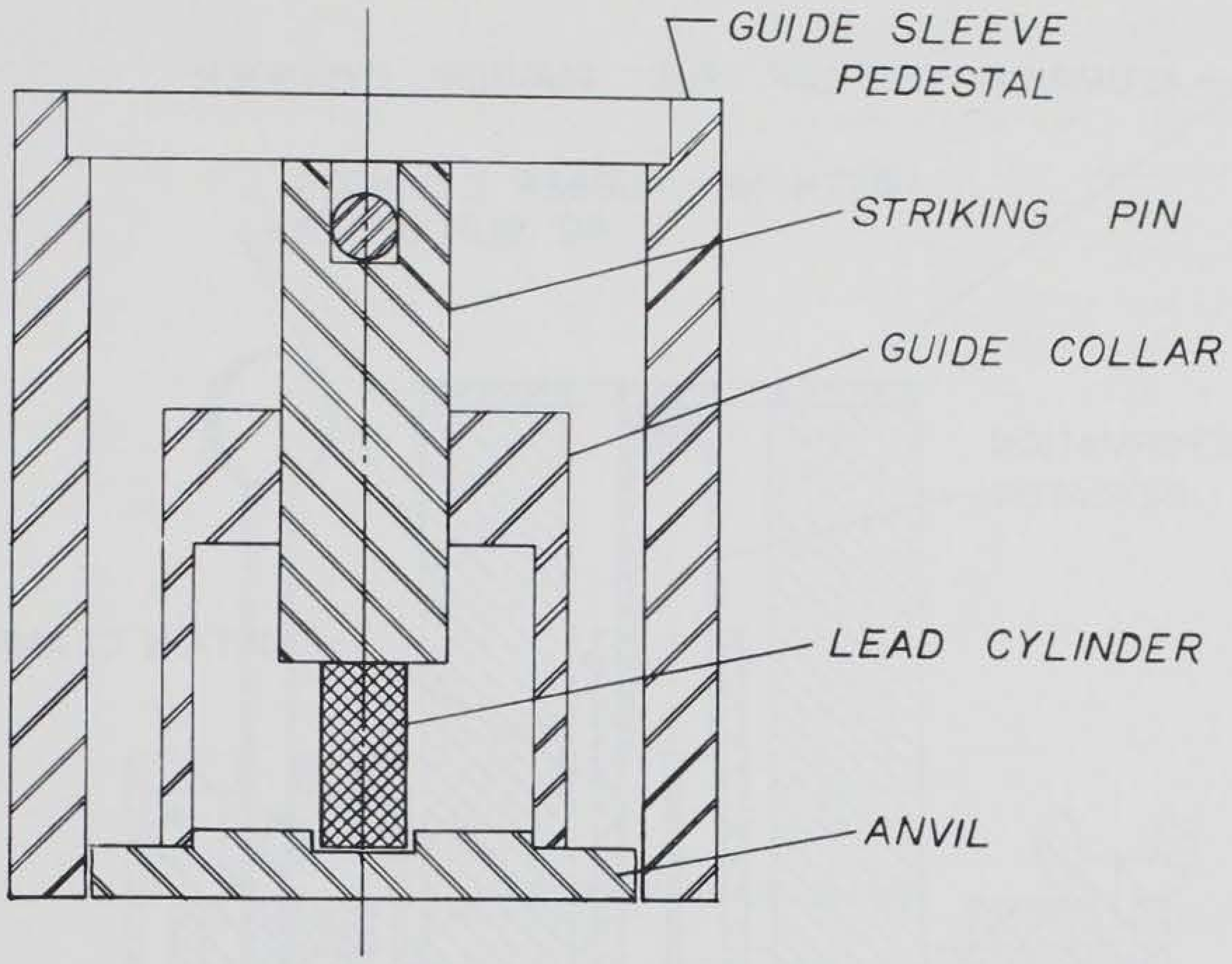


Figure 6. ASTM lead cylinder deformation apparatus

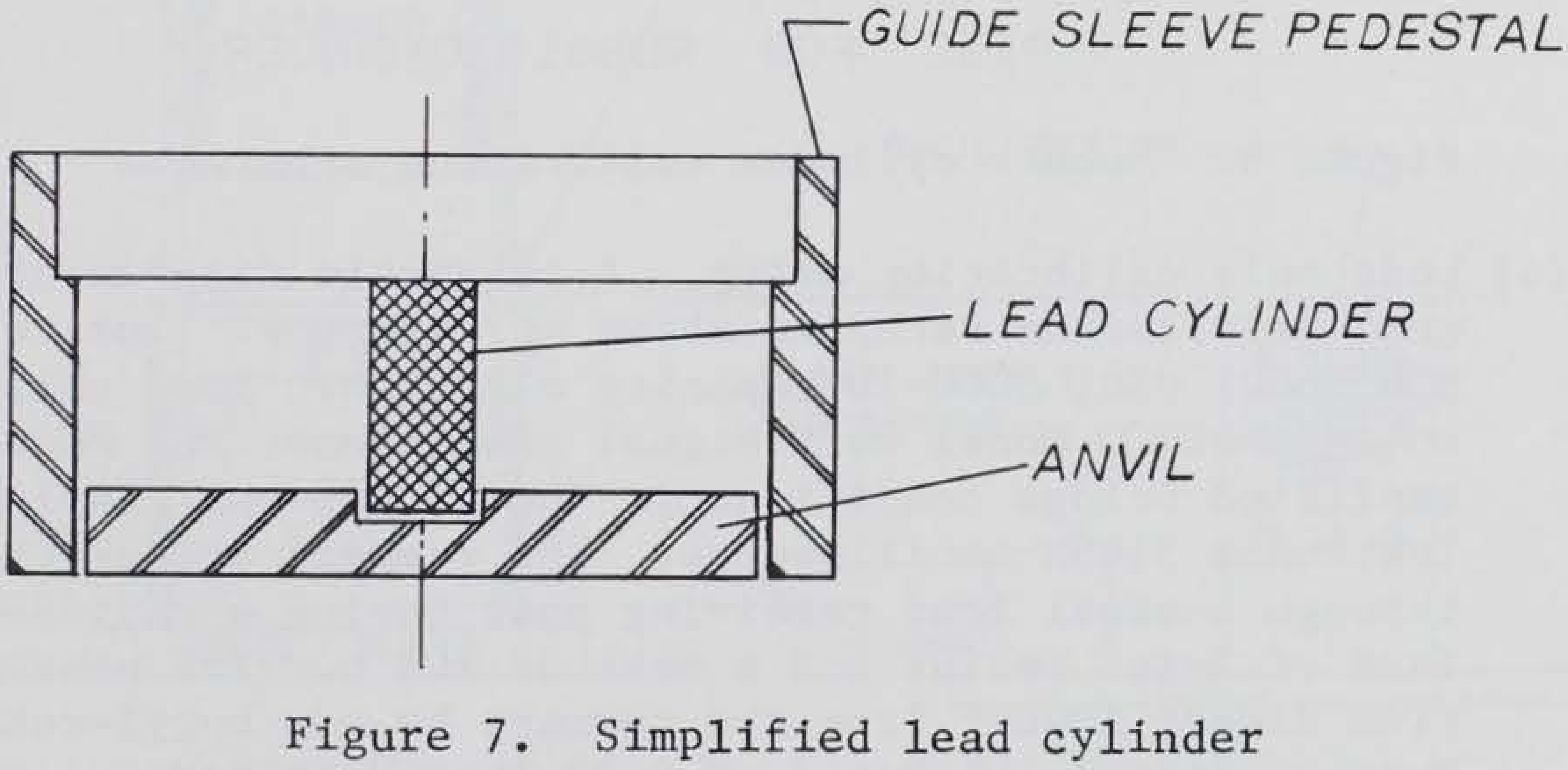


Figure 7. Simplified lead cylinder deformation apparatus

(3) Rubber-cylinder calibration apparatus. A diagram of the rubber-cylinder apparatus is shown in Figure 8. The rubber cylinder was molded from a chemically cured urethane rubber and had an A durometer hardness of 40. Caps were cemented to each end of the cylinder after molding. The deflections registered on the sliding rod in the center of the device were measured with depth-measuring calipers for this testing program, with the intent of providing a graduated scale for measuring deflections on a revised version if testing proved the suitability of the device. With the setup used, an initial setting of the deflection indicator was made with the rammer at rest on the rubber cylinder.

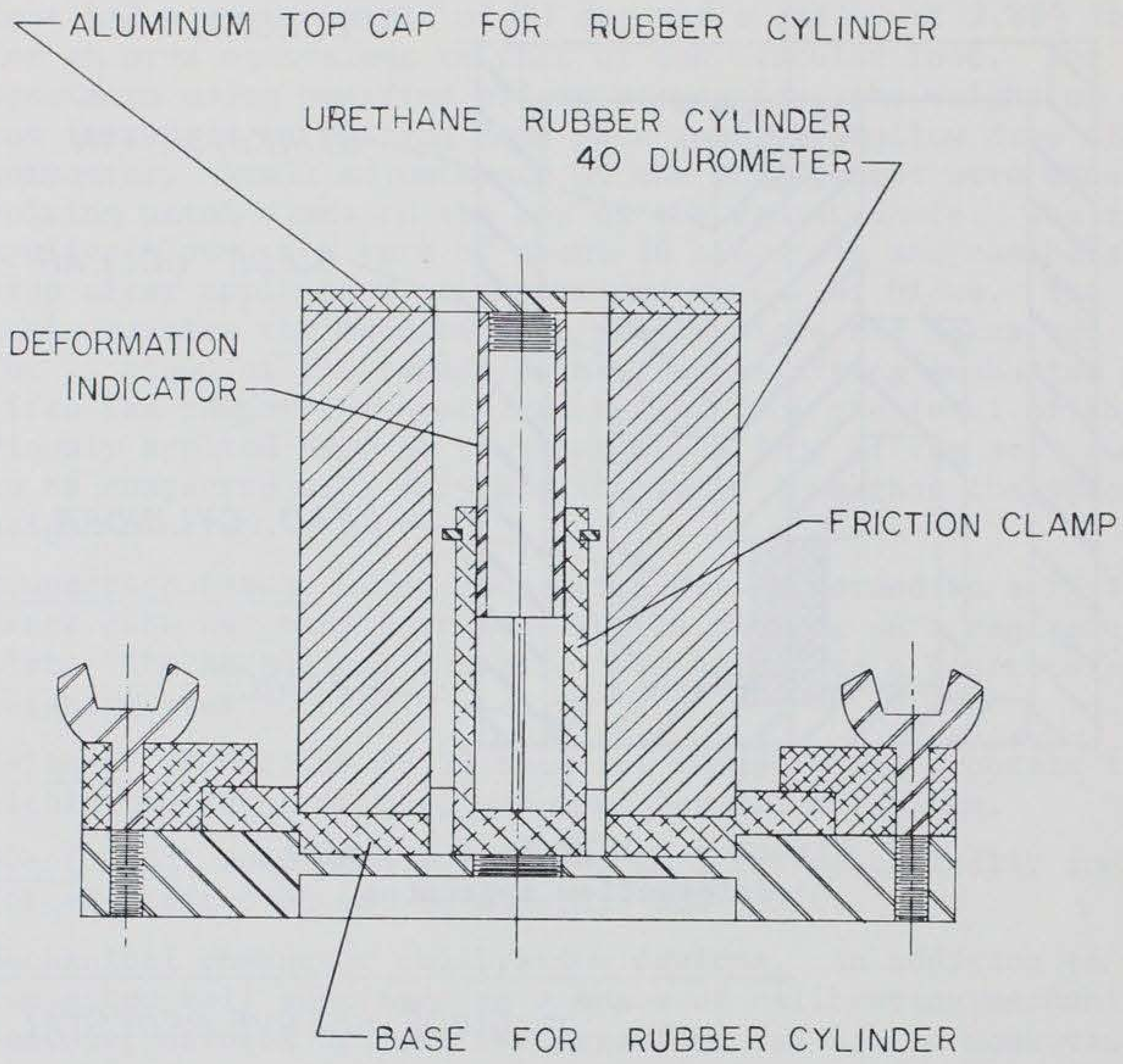


Figure 8. Rubber cylinder calibration apparatus

(4) Load cell calibration setup. A schematic diagram of the load cell calibration setup is shown in Figure 9. The setup used a BLH Model U3G1 5000-lb capacity electronic load cell connected to an ENDEVCO Model 4470 signal conditioner and Model 4476.2 amplified bridge conditioner. The output was displayed on a Tektronix 5103N oscilloscope. The rammers struck the load cell through a steel load receiving post having a radiused striking face of 2-in. radius and a mass of 208 g. The post was cushioned from direct impact from the rammers by two butyl-rubber disks having a total thickness of 0.22 in. When measuring blows from the sleeve rammer, a guide sleeve pedestal was used to maintain the proper height of drop above the rubber disks.

Materials Tested

Source and characterization

32. Six soils were used for the testing program: two fat clays (CH), a brown, lean clay (CL), a light brown silty clay (CL), an orange-brown gravelly clayey sand (SC), and a light gray silty sand (SM). Classification

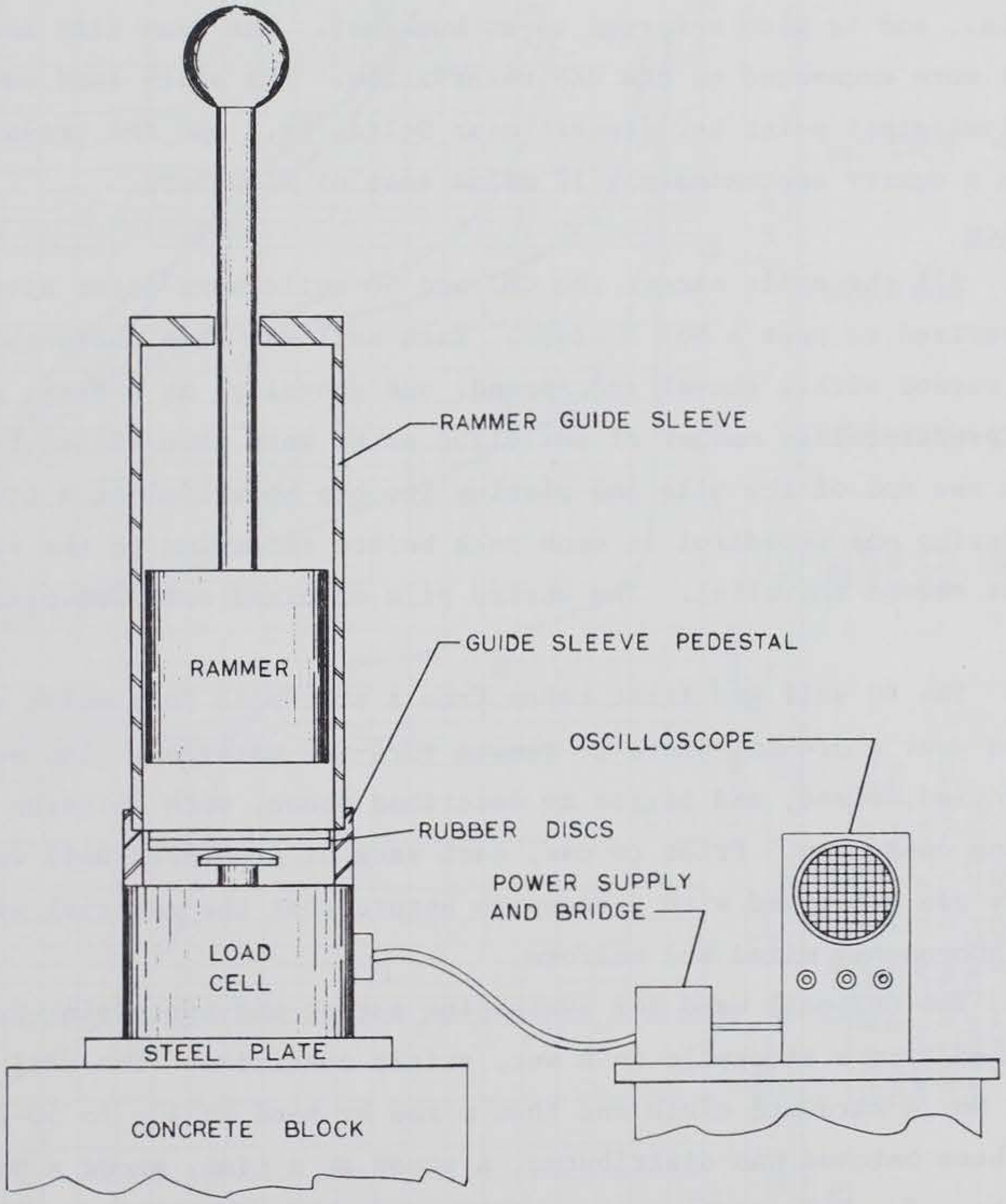


Figure 9. Load cell calibration setup

data for these soils are shown in Figure 10. The fat clay soil having the lower plasticity index (designated CH in Figure 10) and used in most of the testing came from the vicinity of Long Lake, north of Vicksburg, Miss., and is referred to as buckshot. The fat clay used for evaluation of soil processing methods (designated CH2 in Figure 10) came from the vicinity of Mounds, La., and is also referred to as buckshot. The lean clay and silty clay soil were excavated on the WES reservation. The silty sand was taken from a Mississippi point bar deposit near Delta, La., and the gravelly clayey sand from a quarry approximately 10 miles east of Vicksburg.

Preparation

33. All the soils except the CH2 and SC soils were first air-dried and then pulverized to pass a No. 4 sieve. Each soil was then thoroughly mixed by being turned with a shovel and spread, one shovelful at a time, into a long pile. A predetermined number of soiltight sacks were then filled by scooping soil from one end of the pile and placing it, one shovelful at a time, in the sacks, putting one shovelful in each sack before returning to the first sack to add the second shovelful. The entire pile of mixed soil was placed in the sacks.

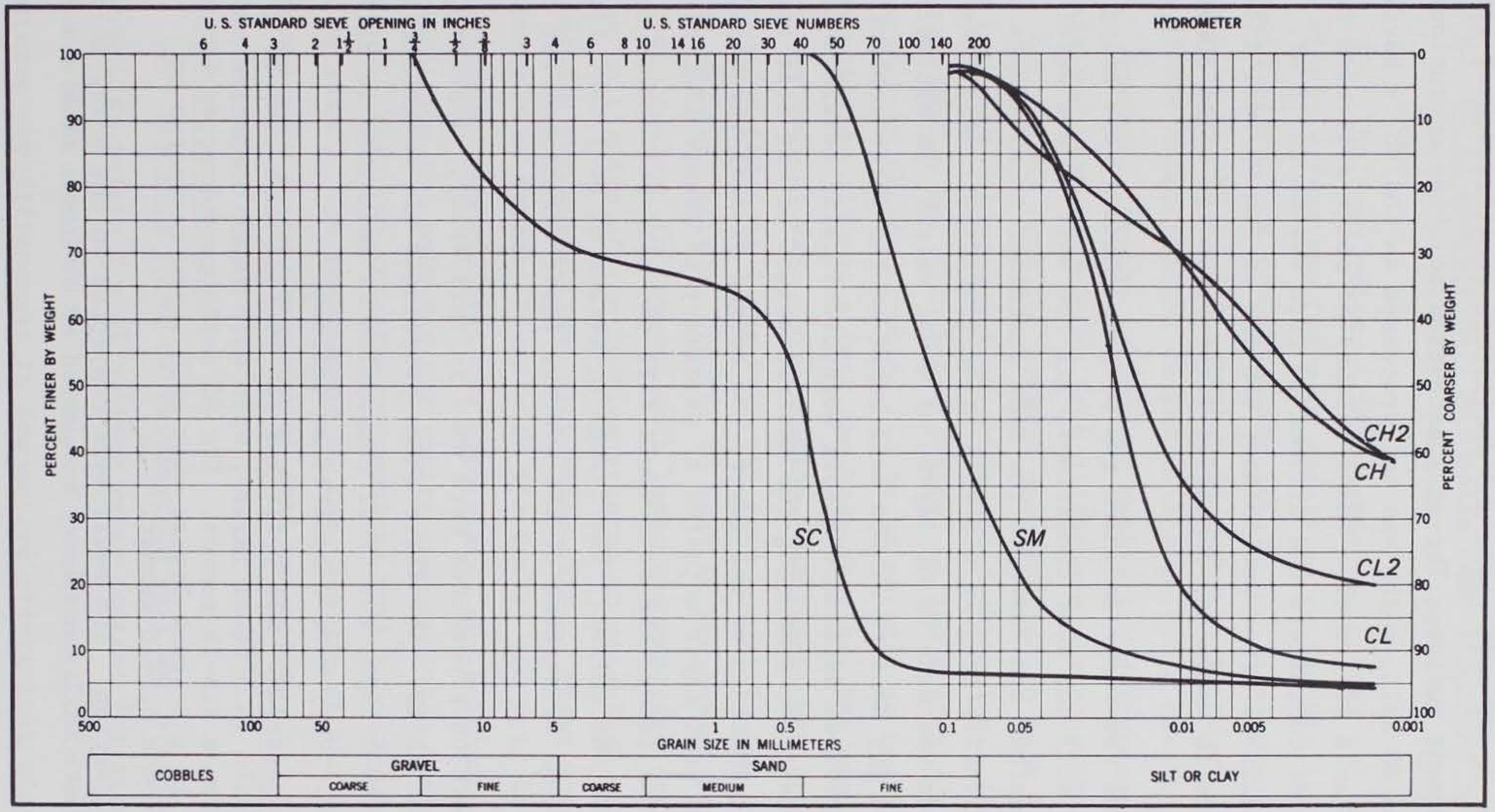
34. The SC soil was first taken from a stockpile in a moist condition and worked over a 3/4-in. sieve to remove +3/4-in. material. The soil was then air-dried, mixed, and bagged as described above, with omission of the pulverizing operation. Prior to use, each sack of processed soil was spread in a large pan and mixed with a scoop to assure that the material within each sack was thoroughly mixed and uniform.

35. The CH2 soil used for evaluating curing and processing procedures was obtained from a stockpile in a wet, sticky condition. The soil was pushed through a No. 4 hardware cloth and then mixed by hand in 40- to 50-lb batches. Each of these batches was distributed, a scoop at a time, among a predetermined number of metal storage cans. After distributing all the soil to the storage cans, the cans were sealed until the soil was needed.

Procedures

Evaluation of manual rammers

36. For this part of the study, compaction curves were developed for each of the rammers, using each of the five soils. To prepare soil for



IDENTIFICATION	CLASSIFICATION	SG	LL	PL	PI
CH	DARK BROWN, FAT CLAY (CH)	2.68	56	19	37
CH2	DARK BROWN, FAT CLAY (CH)	2.70	61	20	41
CL2	BROWN, LEAN CLAY (CL)	2.72	41	19	22
CL	LIGHT BROWN, SILTY CLAY (CL)	2.73	30	21	9
SC	ORANGE-BROWN, GRAVELLY CLAYEY SAND (SC)	2.64	18	13	5
SM	LIGHT GRAY, SILTY SAND (SM)	2.68	Nonplastic		

Figure 10. Classification test results for soils used in study

compaction, amounts of water calculated to produce the desired water content were added to batches of the air-dried soil and the batches mixed in a commercial food mixer. These batches were then pressed through a No. 4 hardware cloth to break up the moist soil clods and facilitate equalization of water content during subsequent curing. The only exception to these operations was in preparation of the SC soil, which was not processed on the No. 4 hardware cloth due to the presence of gravel. These batches of moist soil were then sealed in moisturetight containers and allowed to cure for 66 to 78 hr. This curing time was established after preliminary testing on the CH soil indicated that small differences in compacted densities might occur for soils cured a shorter period.

37. For most of the tests in which two or more rammers were being compared using the same soil and test conditions, all the soil at one water content was mixed together and cured in the same container to eliminate as much as possible any variability in the soil being compacted. To assure that the compacted specimen was made up of layers of equal weight, an estimate was made of the compacted dry density of the soil based on the water content of the mixed soil and previous data on the soil moisture-density relationship. This was used as a basis for computing the desired weight of wet soil for the first layer. After compaction of the layer, the height of soil was measured and the weight of the next layer adjusted if necessary to assure that after compaction of the final layer, the soil would fill the mold but extend no more than 1/4 in. into the collar. The change in weight of soil used for each layer was less than 10 percent of the average layer weight and was usually much less than this.

38. Four compaction procedures were used in this study: standard, 15-blow, modified, and CE-12. The first three procedures are described in Engineer Manual EM 1110-2-1906, and CE-12 compaction is described in Military Standard MIL-STD-621A. They were conducted as follows:

a. Standard compaction. All soils but the SC soil were compacted in the 4-in. mold in 3 equal layers, with each layer compacted by 25 blows from a 5.5-lb rammer. The SC soil was compacted in the 6-in. mold in a 3 equal layers with each layer compacted by 56 blows from a 5.5-lb rammer.

b. 15-Blow compaction. The soils were compacted in the 4-in. mold in 3 equal layers with each layer compacted by 15 blows from a 5.5-lb rammer.

c. Modified compaction. All soils but the SC soil were compacted in the 4-in. mold in 5 equal layers with each layer compacted by 25 blows from a 10-lb rammer. The SC soil was compacted in the 6-in. mold in 5 equal layers with each layer compacted by 56 blows from a 10-lb rammer.

d. CE-12 compaction. All soils were compacted in the 6-in. mold in 5 equal layers with each layer compacted by 12 blows from a 10-lb rammer.

39. The 6-in.-diam, 4.58-in.-high mold used for CE-12 compaction differs slightly from the CBR mold specified in the Military Standard, since the CBR mold produces a compacted specimen 6 in. in diameter and 4.50 in. high. Compacting in the 4.58-in.-high mold resulted in about 2 percent less compactive effort being applied to the soil than would have been applied in the CBR mold. However, for the purpose of evaluating differences between compaction rammers and test procedures, the difference was considered negligible.

40. Blows from the rammers were applied to each layer in a fixed pattern for each mold-compaction procedure combination. The pattern was circular for both molds, but with blows applied in the center after each circuit when compacting in the 6-in. mold. To be as certain as possible that operator idiosyncrasies did not affect the test results, the rammers were operated in a very methodical way. In operation, the rammer was placed at the desired location on the soil layer with the drop weight in the down position. The weight was then raised, brought to rest at the top of its travel, and released. The time required to compact each layer was recorded for an extended period at the initiation of the testing program to establish a reference rate-of-blow application for comparisons with other rates. After completion of compaction, specimens were trimmed flush with the top of the mold using a bevelled straightedge, removed from the base plate, and weighed. The specimen was then extruded from the mold and the entire specimen used for water content determination. The time required to complete work on each compaction specimen was also recorded. The temperature of the room and of the soil being tested were taken whenever a new container of soil was opened.

Evaluation of effect of rate-of-blow application

41. For this phase of testing, CH soil was prepared at approximately 4 percentage points dry of optimum water content for standard effort compaction and CE-12 compaction. Soil was prepared at this water content to accentuate any differences in compactive effort that might be applied by the

rammers at different rates and to eliminate the problem of the foot of the sliding-weight rammers sticking to the soil and preventing the rapid application of blows. Two operators were used: Operator B who performed most of the compaction tests on the project and Operator C, a less experienced operator used for just this phase of testing. Each operator compacted 5 specimens using the 5.5-lb sleeve-type rammer and increasing his rate-of-blow application for each specimen from a moderate rate on the first point to his fastest attainable rate on the third and fourth points. The fifth point was compacted using the slow rate of compaction used for evaluating the rammers during the first phase of the study. The operator then compacted five more specimens in the same way using the new 5.5-lb sliding-weight rammer, followed by the two 10-lb rammers and CE-12 compaction effort. Finally, Operator B obtained 5 compaction points using the 5.5-lb solid foot sliding-weight rammer to provide data for reference with past studies.

Evaluation of preparation and curing procedures

42. In this phase of testing, compaction curves on the CH2 soil were developed using the 5.5-lb sleeve rammer at standard compaction. Starting at a water content of about 34 percent, the soil was prepared for compaction in one of six ways:

a. Air-dry fully, pulverize to pass through a No. 4 hardware cloth, mix water with individual batches of dried soil to get desired compaction water contents, press through a No. 4 hardware cloth, and cure for three days.

b. Air-dry to approximately 6 percentage points below optimum water content, push through a No. 4 hardware cloth, mix water with individual batches of partially dried soil to get desired compaction water contents, press through a No. 4 hardware cloth, and cure for three days.

c. Separate soil at natural water content (above optimum) into batches and dry each batch a different amount to arrive at a spread in water contents for compaction. Press through a No. 4 hardware cloth, and cure for three days.

d. Repeat the steps given in a but eliminate the cure time of three days. Compact immediately after passing through the hardware cloth.

e. Repeat the steps given in b but eliminate the cure time of three days.

f. Repeat the steps given in c but eliminate the cure time of three days.

Effect of sector-shaped foot on density and CBR

43. For this phase of testing, compaction curves were developed for each of the five soils using both the mechanical rammer equipped with the sector-shaped foot and the corresponding manual sleeve rammer. It would have been desirable to compare the results produced by the mechanical rammer equipped with the circular foot with those produced by the same mechanical rammer using the sector foot. However, the mechanical rammer used for this study was not designed to permit evenly distributing blows over the surface of the soil when using the 6-in. mold and round foot. Compaction curves were developed for both standard and modified compaction as described in Engineer Manual EM 1110-2-1906 except that all specimens were compacted in 6-in.-diam CBR molds using a spacer that produced a specimen height of 4.58 in. After compaction, the unsoaked CBR of each specimen was determined using the procedure given in Military Standard MIL-STD-621A.

44. Prior to the standard effort compaction tests, the mechanical rammer equipped with the circular foot was calibrated using both soil and lead test cylinders in the simplified apparatus. For the calibration using soil, duplicate specimens of CH soil were compacted in the 4-in. mold at about 3 percentage points dry of optimum water content, and results compared to the results produced by the manual rammer. The mechanical rammer's drop weight was then adjusted by adding weight to the drop shaft until the results were the same as those given by the manual. This required a drop weight of 6.00 lb. After the correct drop weight was determined for the mechanical rammer equipped with the circular foot, lead cylinder deformation trials were performed using the mechanical rammer; the circular foot was then replaced with the sector foot and additional trials were performed. The mechanical rammer was further adjusted so that the average of the lead cylinder deformations when using the sector foot was approximately the same as the average obtained when using the circular foot. This resulted in a drop weight of 6.40 lb which was used for all the standard compaction tests for this phase of testing.

45. The purpose of calibrating the mechanical rammer in this way was to determine whether switching to the sector foot from the circular foot without any other change, would have an effect on compaction results. This was done with the intent of separating the effect of the shape of the foot

from other variables that may have been associated with changing from one foot to another, e.g., the rigidity of the particular sector foot design used.

46. Prior to using the sector foot in modified effort compaction, the mechanical rammer was recalibrated by setting the height of drop at 18 in. (while in operation) and the drop weight at 10.0 lb. In this case, however, the mechanical rammer was calibrated using soil while equipped with the sector foot and the drop weight was adjusted to produce the same compacted densities as were obtained using the manual rammer. A drop weight of 12.00 lb was required.

Calibration of mechanical rammer

47. Before this phase of testing was started, the mechanical compactor was cleaned and lubricated as indicated in the operating instructions, and the machine was leveled so that the drop shaft was vertical. The drop weight was adjusted to be 5.5 lb by putting washers on the bolts that hold the tamping foot to the shaft and by attaching thin metal disks to the top of the drop shaft.

48. The height of drop was measured during operation using a cathetometer (an optical sight tube mounted on a graduated vertical shaft, capable of measuring differences in height to 0.01 cm). Using the cathetometer, the operating height of drop was adjusted to 12.0 in.

49. Calibration using soil. It was shown by McRae and verified in this study that soils of higher plasticity show the greatest response to differences in compaction effort (McRae 1959). Consequently, the CH soil used in the rammer verification tests was used for calibration of the mechanical compactor. Duplicate curves were compacted at standard effort using the sleeve rammer and the mechanical compactor adjusted to 5.5 lb and 12.0-in. drop as described in the previous paragraph. The height of drop of the compactor was then adjusted using the deformation of lead cylinders in the ASTM apparatus as a guide. The height of drop after adjustment was 12.8 in. Two more compaction curves were produced. Soil preparation and compaction procedures used for this phase of testing were identical to those used in the rammer verification tests. Before beginning compaction of each layer of soil using the mechanical rammer, the drop shaft of the rammer was gently lowered to the loose soil surface so that the height of drop was referenced to the new soil layer rather than the previous one.

50. Calibration using air-dry soil or granular material. The procedures used for compacting these materials were the same as used for the

rammer verification tests except that the adding water, mixing, and curing operations were omitted.

51. Calibration using devices that measure individual rammer impacts. Each device was tested by applying blows from the 5.5-lb sleeve rammer and then repeating the operation using the mechanical rammer set to 12.0-in. height of drop. The mechanical rammer was then adjusted to 12.8-in. height of drop and another series of rammer impacts was measured by each device.

PART III: RESULTS AND DISCUSSION

Evaluation of Manual Rammers

Preliminary tests to develop new sliding-weight rammers

52. An initial design 5.5-lb sliding-weight rammer with low-mass spring-loaded foot was fabricated and given preliminary testing in standard effort compaction tests on the CH soil. This rammer produced a maximum dry density 2.4 pcf lower than that produced by the sleeve rammer. The prototype was then redesigned to lower the mass of the foot and to soften the spring as much as practicable, commensurate with durability. This design was adopted (see Figures 1 and 2) for formal evaluation after further testing showed a result within 1.2 pcf of that produced by the sleeve rammer.

53. The new 10-lb sliding-weight rammer was given the same basic configuration as the Military Standard MIL-STD rammer, with a foot like that of the new 5.5-lb rammer, except the wall thickness of the foot was increased to withstand the higher impact stresses of the 10-lb drop weight.

Test results on 5.5-lb rammers

54. Results of standard effort compaction tests on five soils using the sleeve rammer and new sliding-weight rammer were presented in Figures 11-15. Results of tests using the slotted sleeve rammer are also included for the CH, SC, and SM soils (Figures 11, 14, and 15). Results of 15-blow compaction tests on the CH, CL2, and CL soils using the sleeve and new sliding-weight rammer are given in Figures 16-18. A summary of the maximum dry densities and optimum water contents for both the standard and 15-blow tests are given in Table 3. As discussed in the sections evaluating the 10-lb rammers, different parts of this study were conducted by different operators. However, all the evaluation tests on 5.5-lb rammers were conducted by Operator B (the less experienced one).

55. The data show that for both standard and 15-blow compaction, the sleeve rammer produced higher maximum dry densities than the sliding-weight rammer and about equal optimum water contents. The differences were relatively small, however, with the maximum at 0.8 pcf using standard effort on the SC soil. The maximum difference in optimum water content was 0.4 percentage points, using standard effort on the SM soil. The slotted sleeve rammer fell

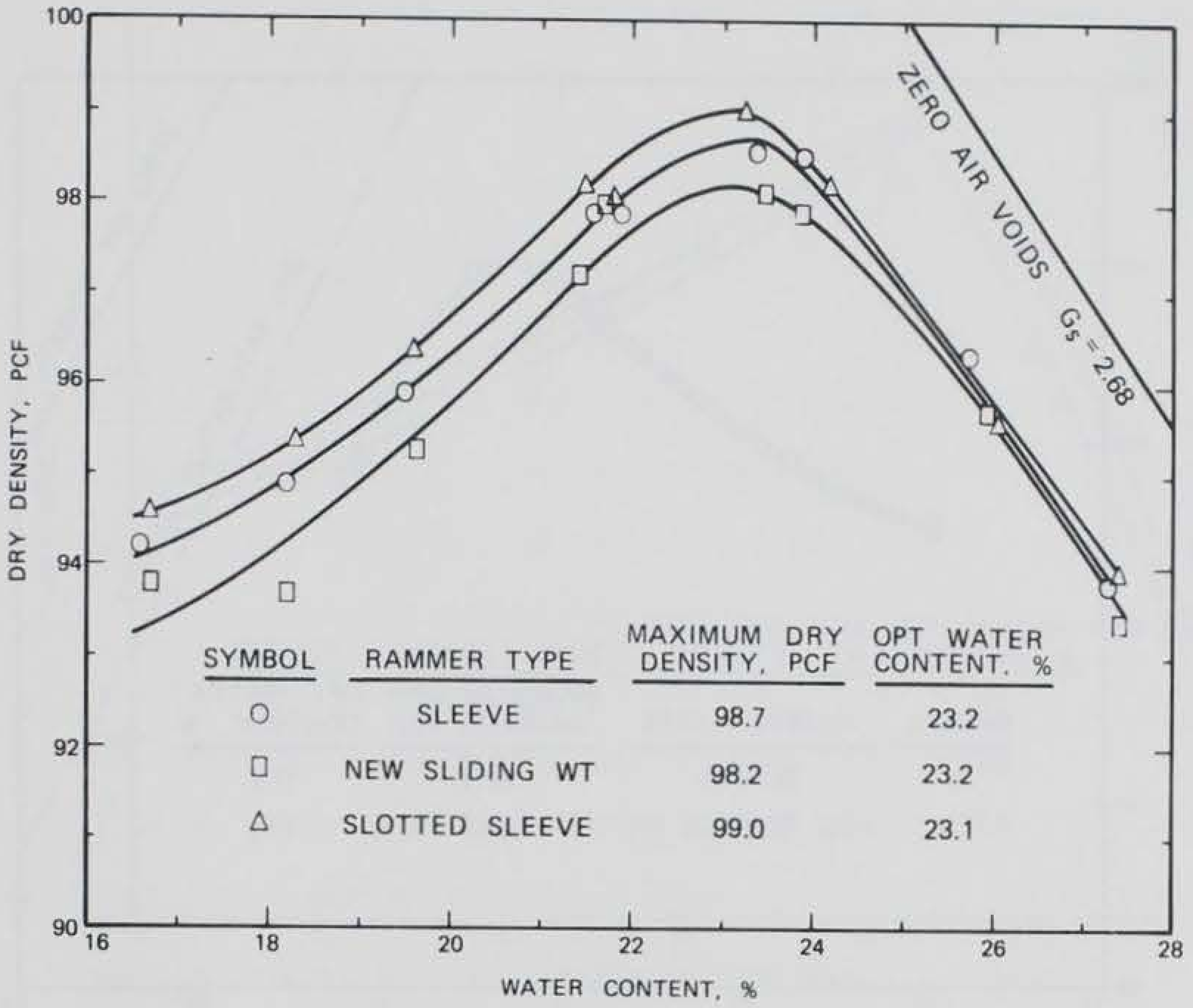


Figure 11. Standard compaction tests on CH soil using 5.5-lb manual rammers

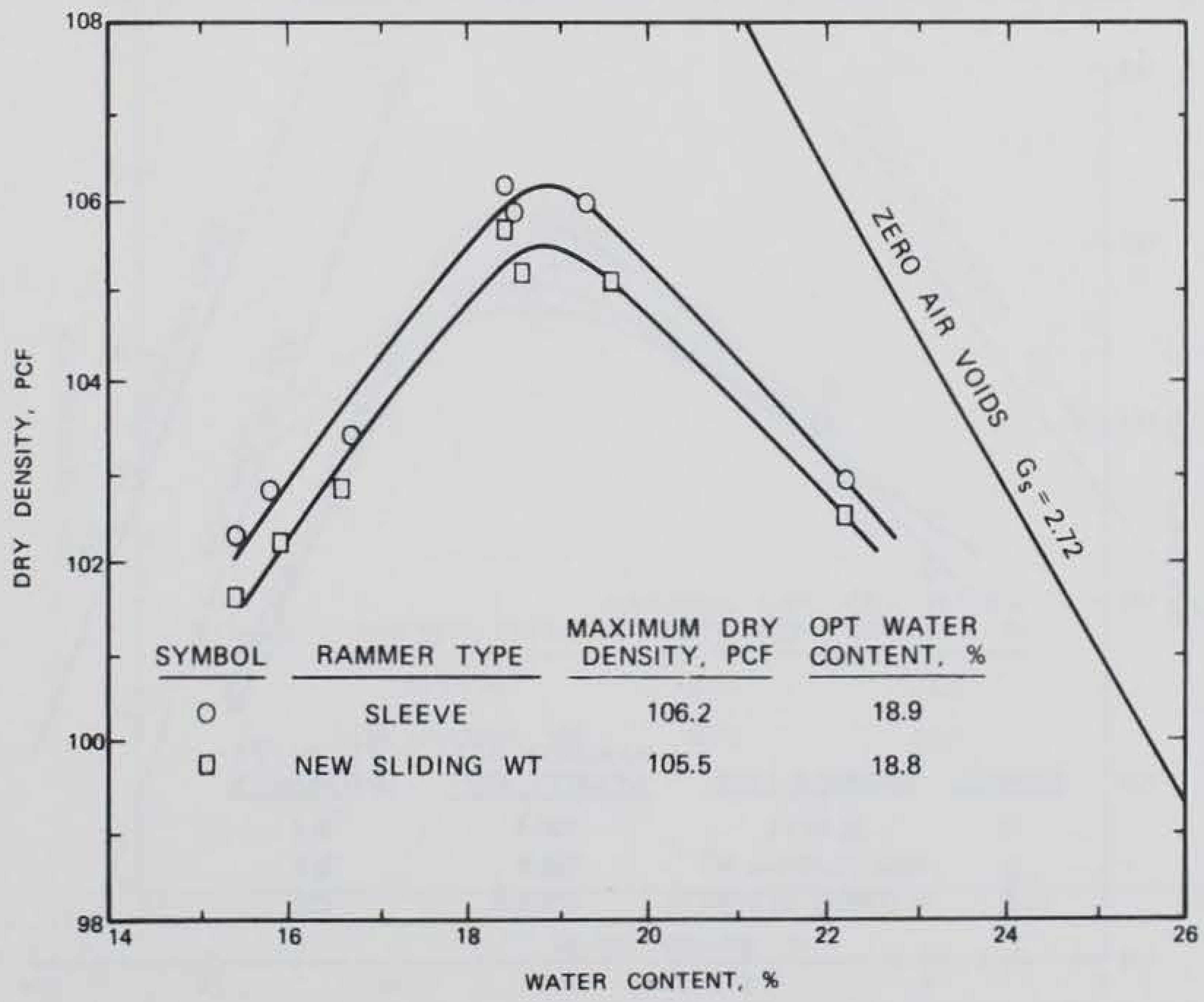


Figure 12. Standard compaction tests on CL2 soil using 5.5-lb manual rammers

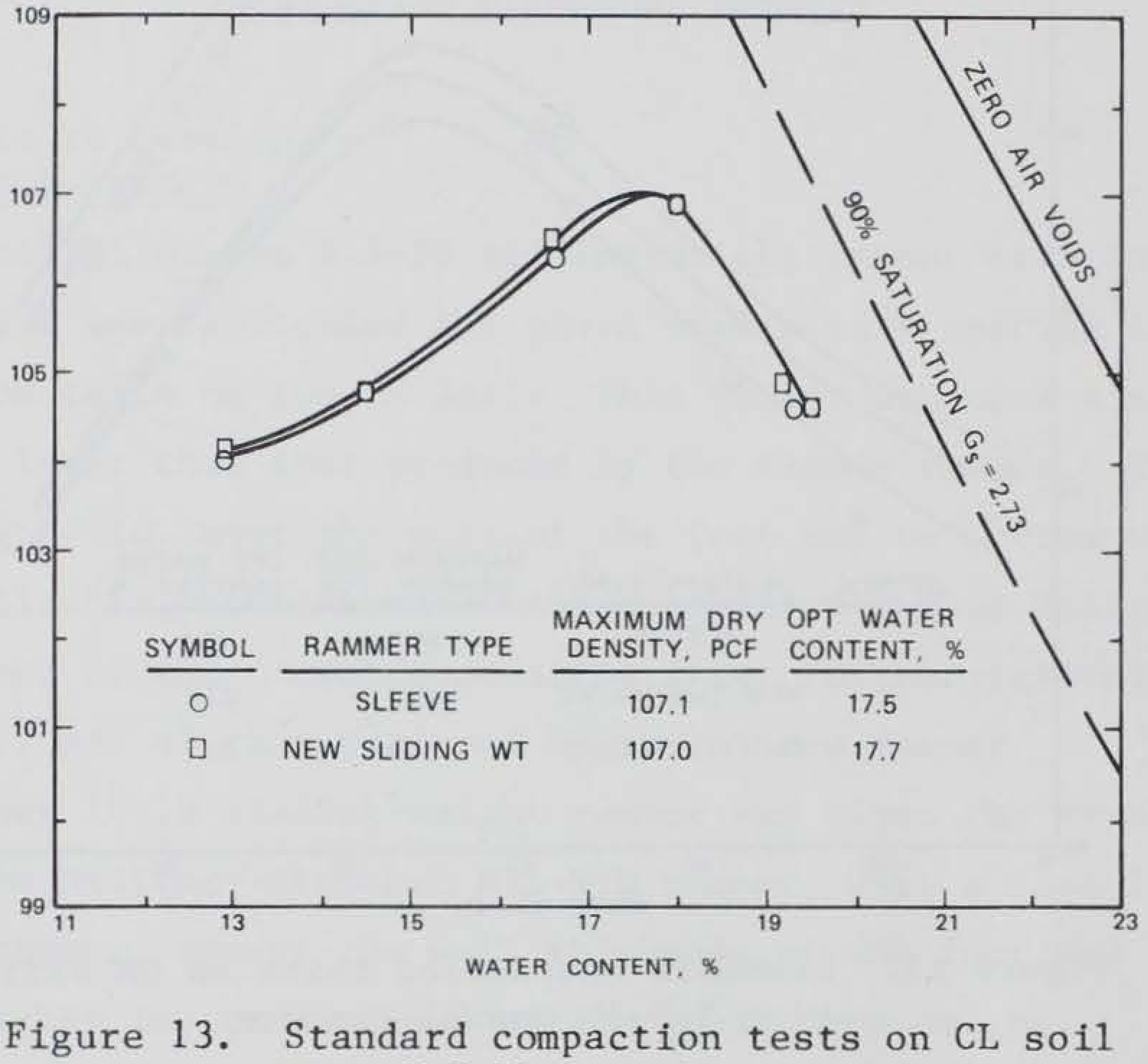


Figure 13. Standard compaction tests on CL soil using 5.5-lb manual rammers

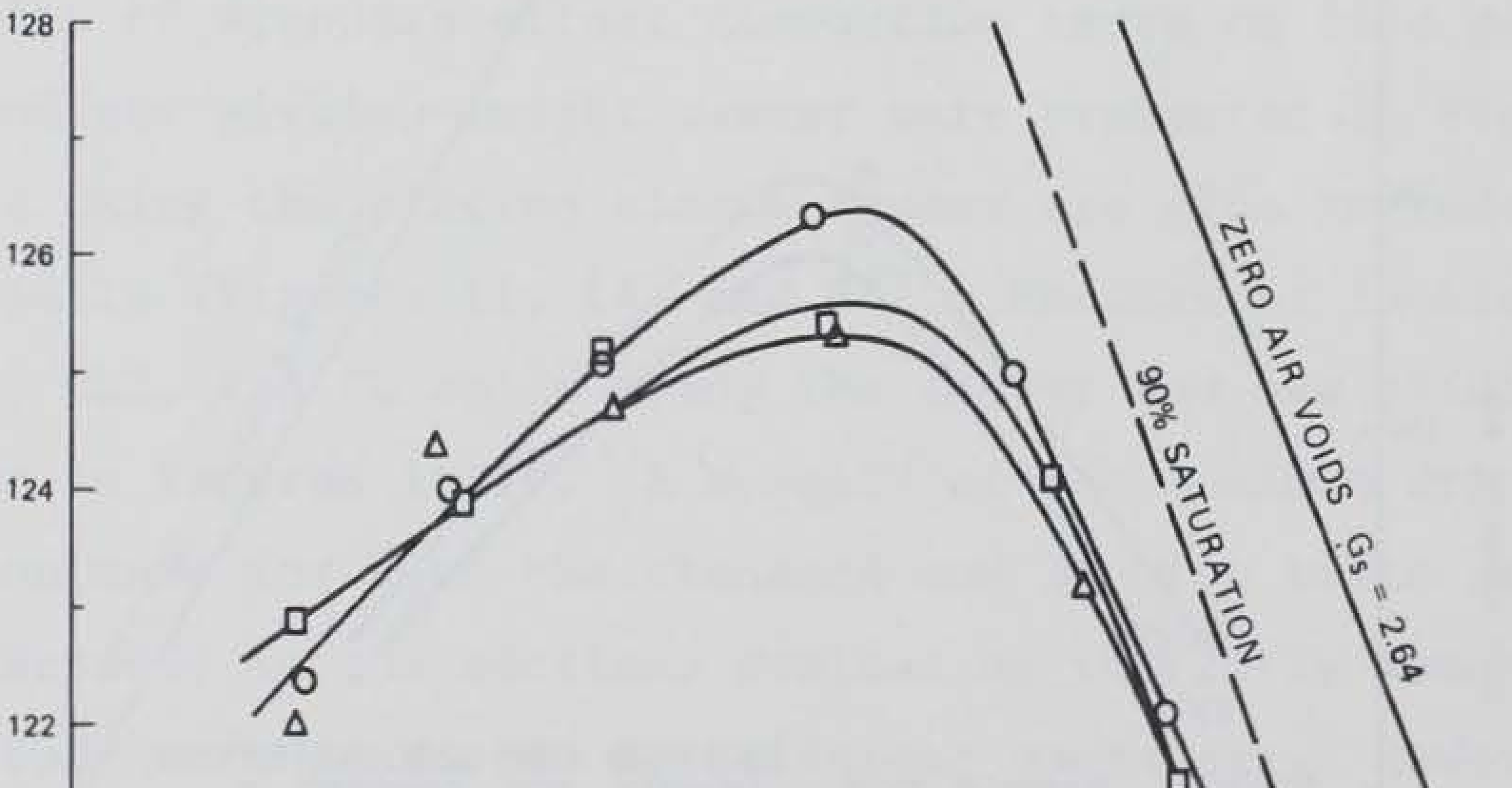


Figure 14. Standard compaction tests on SC soil using 5.5-lb manual rammers

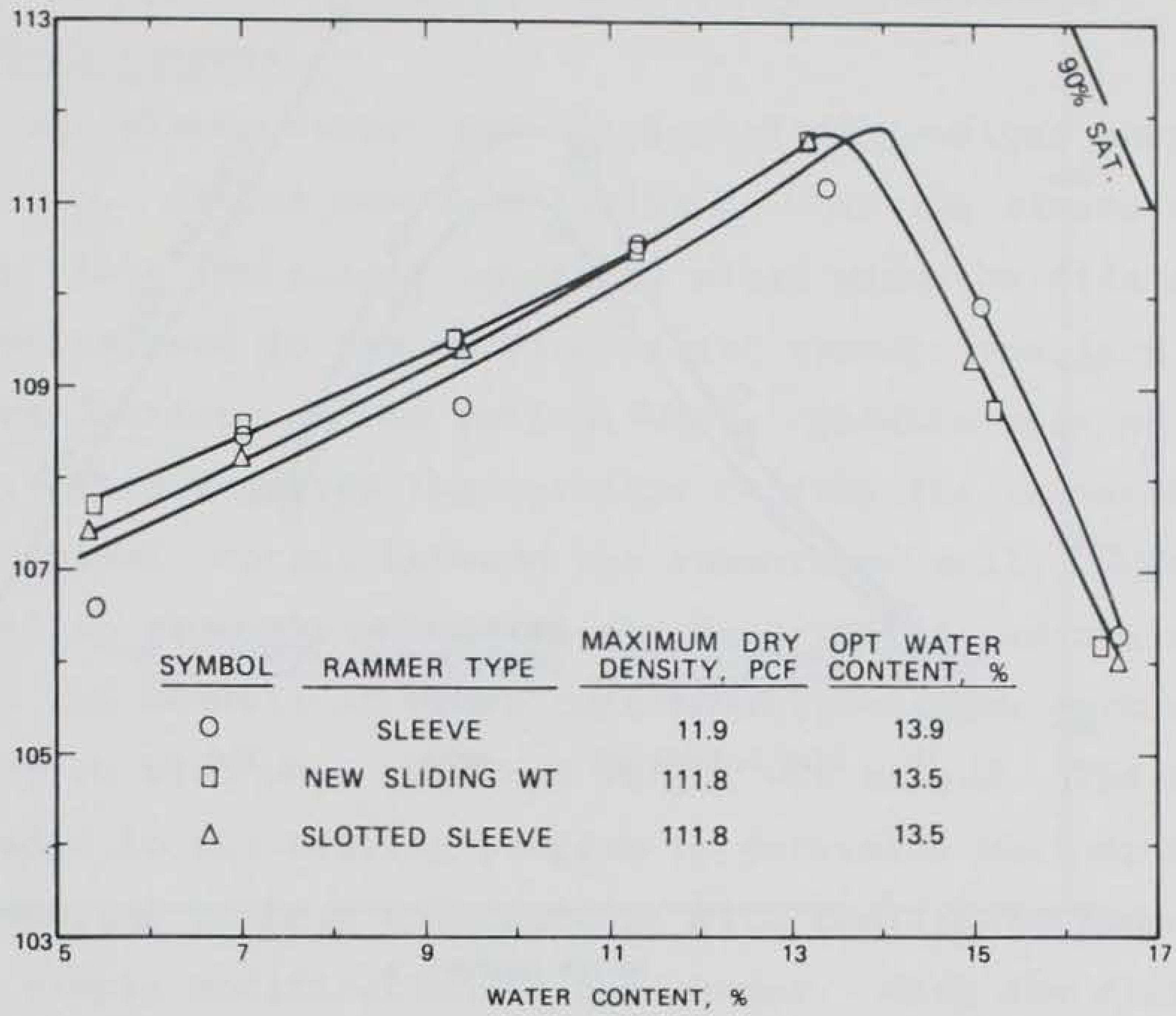


Figure 15. Standard compaction tests on SM soil using 5.5-lb manual rammers

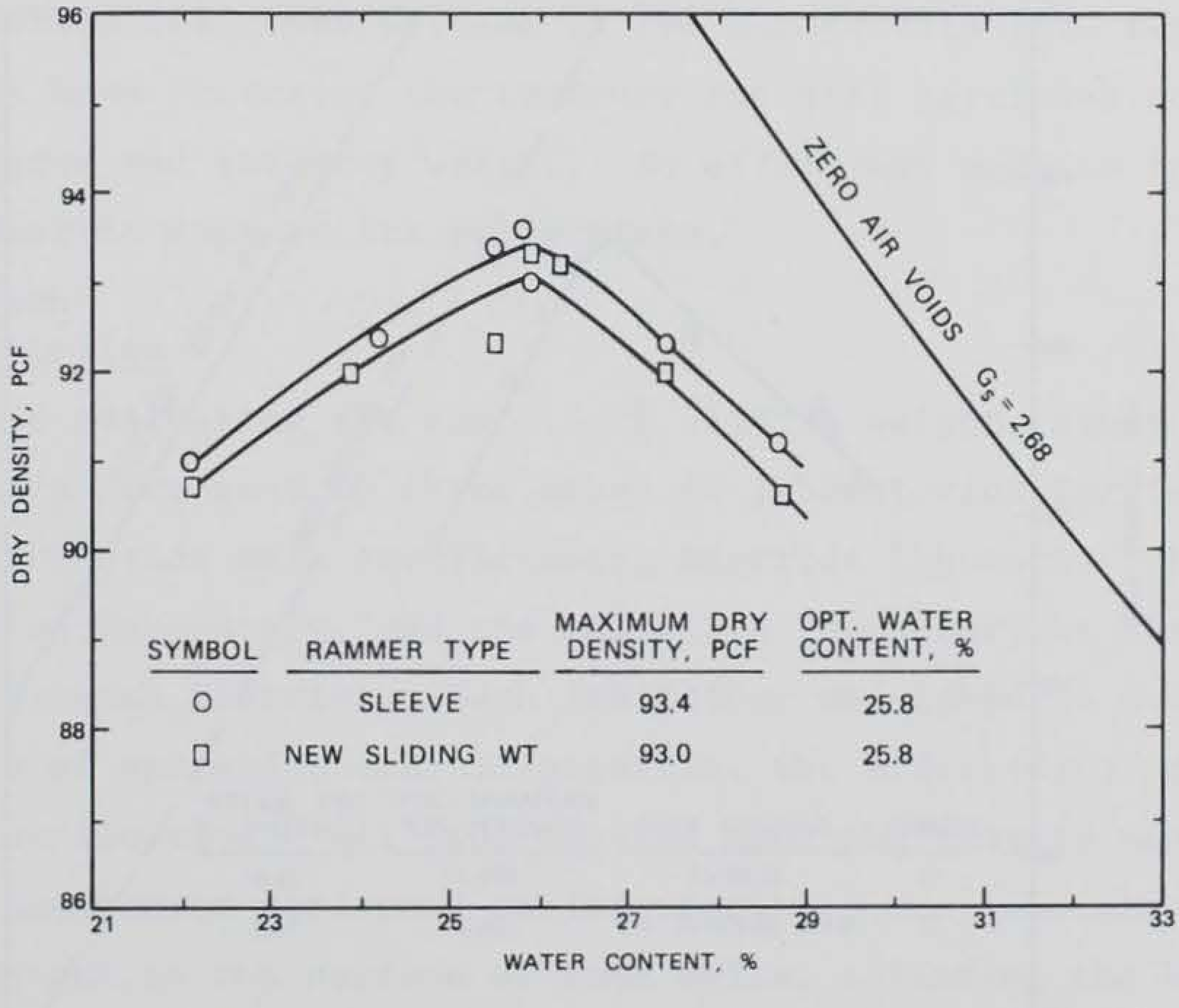


Figure 16. 15-blow compaction tests on CH soil using 5.5-lb manual rammers

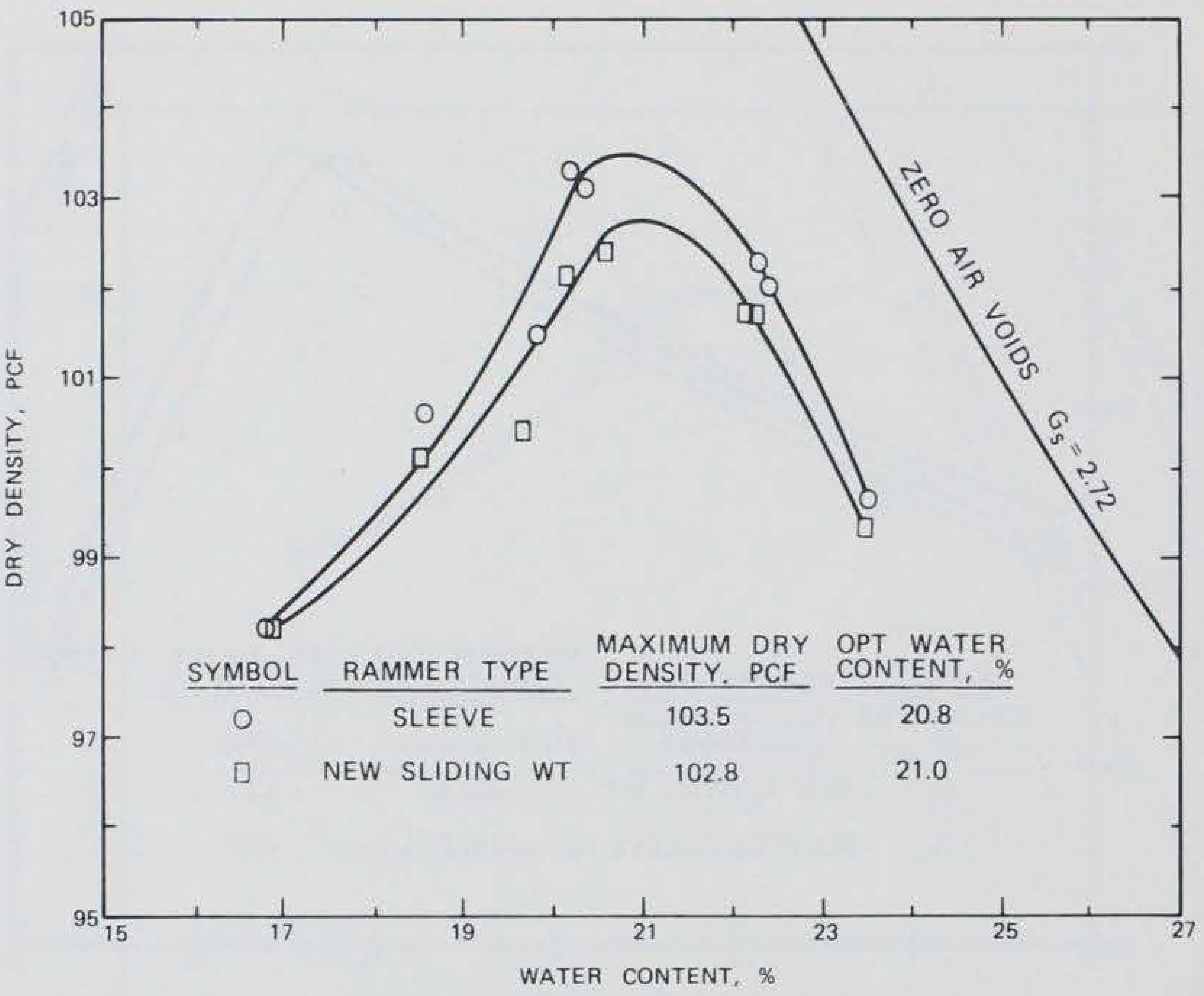


Figure 17. 15-blow compaction tests on CL2 soil using 5.5-lb manual rammers

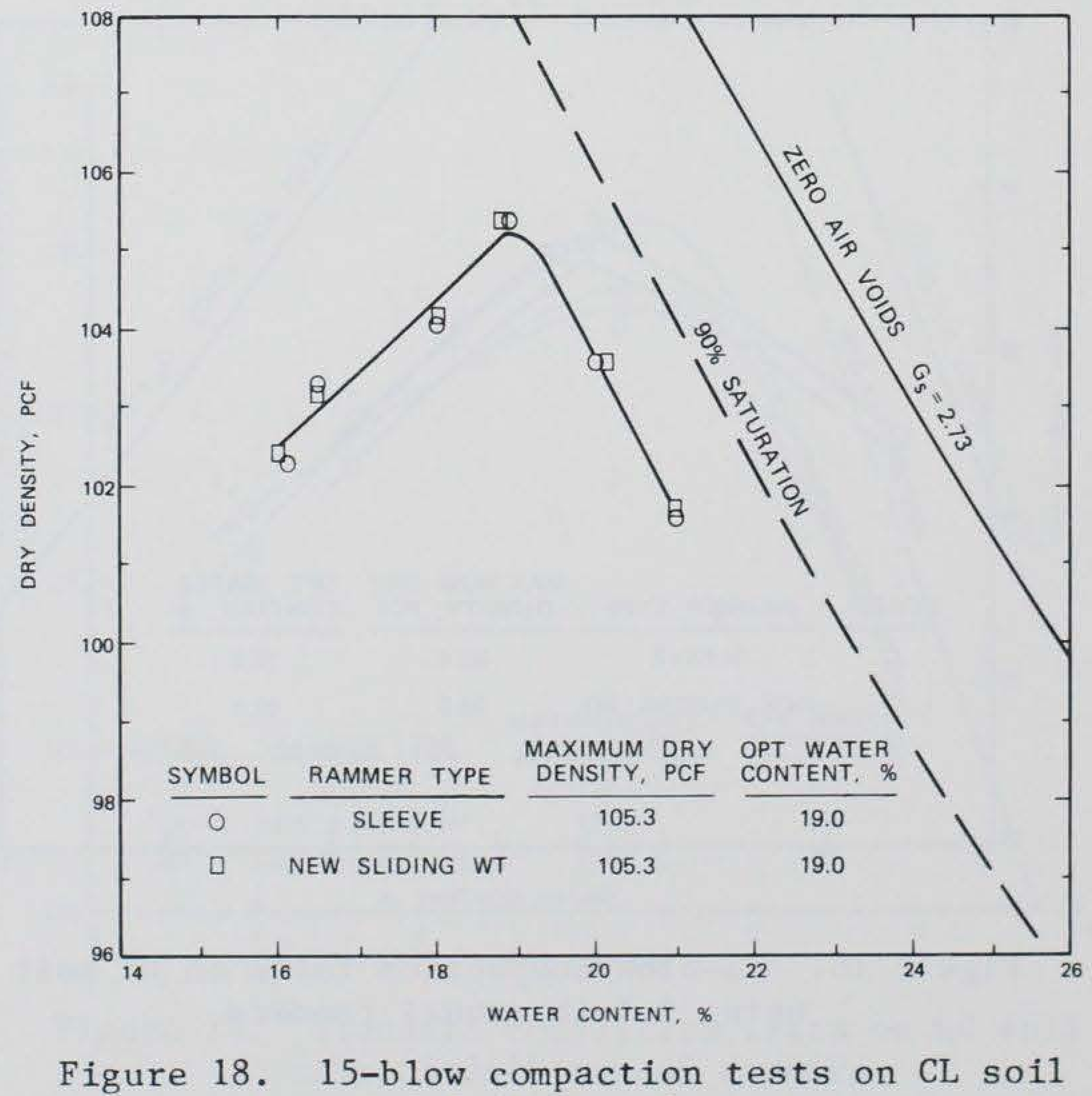


Figure 18. 15-blow compaction tests on CL soil using 5.5-lb manual rammers

0.3 pcf above the sleeve rammer on the CH soil and 1.1 pcf below the sleeve rammer on the SC soil.

Operation of 5.5-lb rammers

56. Both the sleeve rammer and the new sliding-weight rammer were about equally easy to use. It was somewhat easier to keep the sleeve rammer vertical while compacting since the sleeve tended to align with the side of the mold. With the soft spring used in the sliding-weight rammer, the foot would sometimes stick to the surface of the soil at water contents near or on the wet side of optimum. This required the operator to rock the rammer slightly between blows to break contact between the rammer and soil. There was a tendency for soil to accumulate between the drop weight and the sleeve of the sleeve rammer on the SC soil at water contents higher than optimum, causing a slight tendency to bind when the drop weight was raised. The slotted sleeve rammer was included in the testing program to determine whether the binding that had been reported to be a disadvantage with the sleeve rammer could be eliminated by a simple modification to the rammer. With the slotted rammer, there was a slight binding when the drop weight was being lifted on the first few blows of each layer. This may have resulted from the springiness of the prongs which formed the lower portion of the sleeve with this rammer. This springiness may have increased the tendency for soil particles to wedge between the sleeve and the drop weight. No effort was made to further modify the sleeve rammer to improve its performance.

Rammer evaluation by other laboratories

57. After evaluating the new 5.5-lb sliding weight rammer at WES, three prototype rammers were sent to three other CE laboratories for further evaluation. The laboratories were the Vicksburg District Laboratory, the South Atlantic Division Laboratory, and the materials laboratory at the R. B. Russell Dam project, Savannah District. Each laboratory was asked to evaluate the rammer for ease of operation and, if possible, the effect(s) of different rates of blow application. All laboratories used the rammers sent to and all reported that the rammer performed satisfactorily. One laboratory reported that the foot stuck to the surface of some soils, a finding the WES laboratory experienced. None of the rammers broke during the trials and the technicans who operated the rammers stated that the rammers handled well. The evaluation

of the effect(s) of rate of blow application by one laboratory will be discussed later.

Change in operators

58. Part way through this study after most of the tests comparing the 10-lb sleeve, Military, and solid foot rammers had been completed, the technician (Operator A) who had been performing all the compaction tests up to that time retired. To eliminate any variation in the test results due to the change in technicians, the new technician (Operator B) performed the evaluation tests of the new 10-lb sliding-weight rammer using both the sleeve rammer and the new sliding-weight rammer on the five soils rather than relying on data previously collected on the sleeve rammer by Operator A. Thus all the tests performed to evaluate the Military and solid foot rammers relative to the sleeve rammer and all the evaluation tests on the new 10-lb sliding-weight rammer are labeled as being performed by either technician A or B.

Test results on existing 10-lb rammers

59. Initially, evaluation of the 10-lb rammers involved comparison of the sleeve-type rammer with the Military and solid foot sliding-weight rammers. The rammers were tested on five soils using modified and CE-12 compaction.

60. Results of the compaction tests using the 10-lb sleeve, Military, and solid foot sliding-weight rammers are given in Figures 19-23 for modified effort compaction and Figures 24-28 for CE-12 compaction. The data are summarized in Table 4.

61. The data presented in Figure 22 showed considerable scatter. The only observable explanation for the scatter was that the rammer impacts caused disturbance of previously compacted soil, resulting in the reloosening of the previously compacted soil. Data presented in Figure 32 for the same soil and compaction procedure show similar scatter. Additional data were not obtained for the compaction tests in Figure 22 as operator A, who had performed these tests, retired before additional data could be obtained.

62. The data show that the sleeve rammer produced higher maximum dry densities and lower optimum water contents than either the Military or solid foot rammers. The maximum differences for the military rammer were 3.0 pcf maximum dry density on the CH soil using CE-12 compaction, and 0.6 percentage points in optimum water content using modified compaction. The maximum

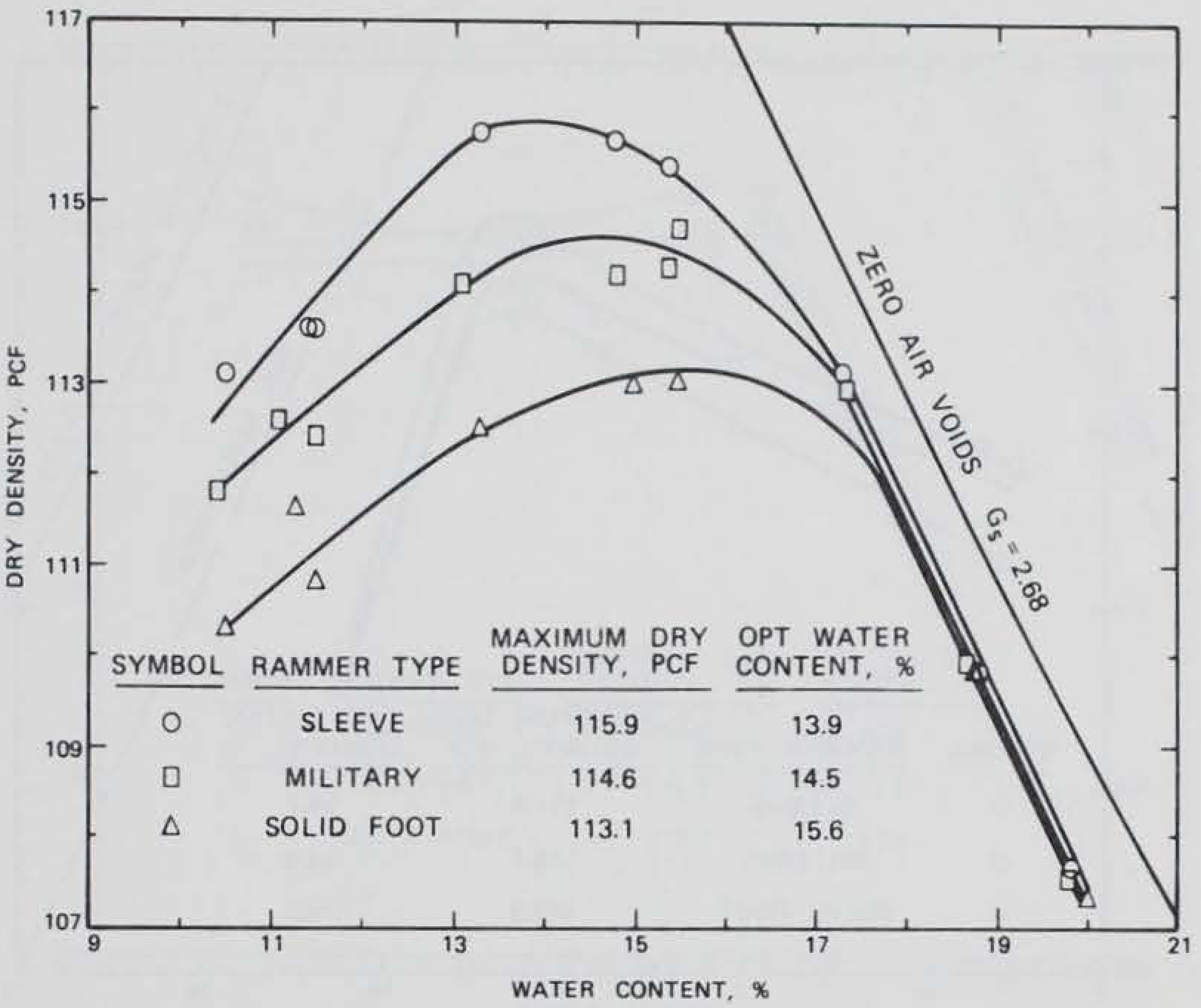


Figure 19. Modified compaction tests on CH soil using existing 10-lb manual rammers

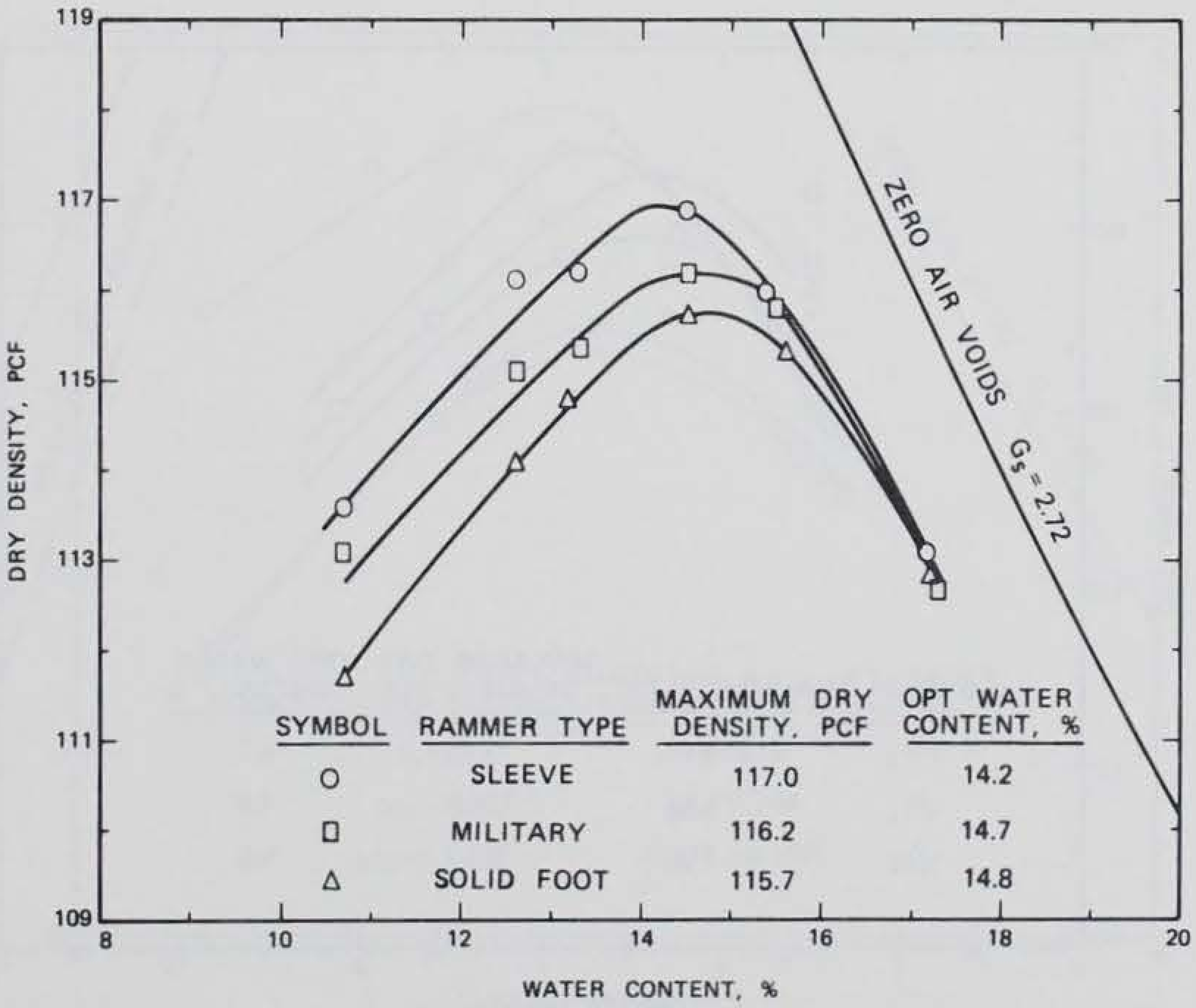


Figure 20. Modified compaction tests on CL2 soil using existing 10-lb manual rammers

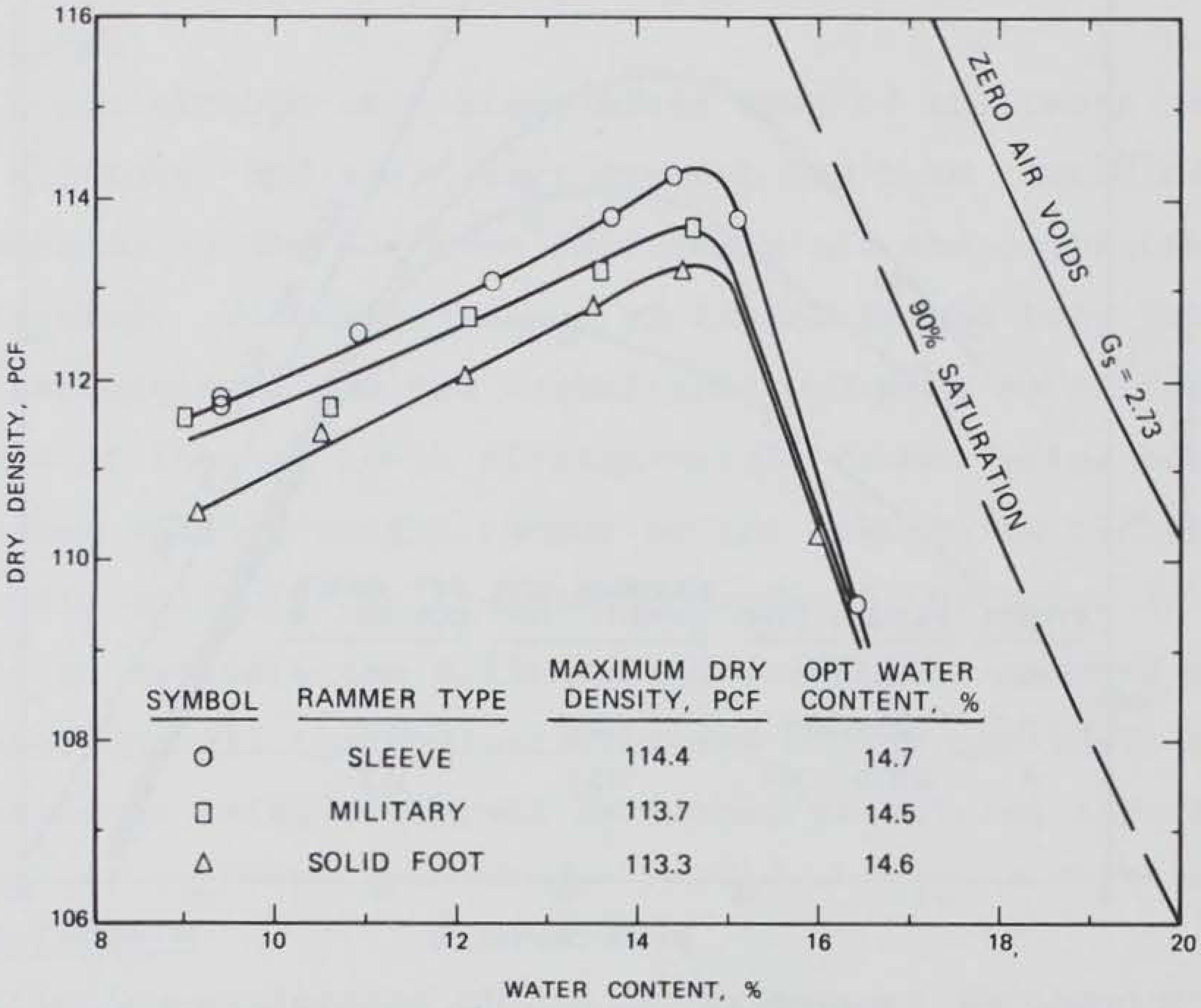


Figure 21. Modified compaction tests on CL soil using existing 10-lb manual rammers

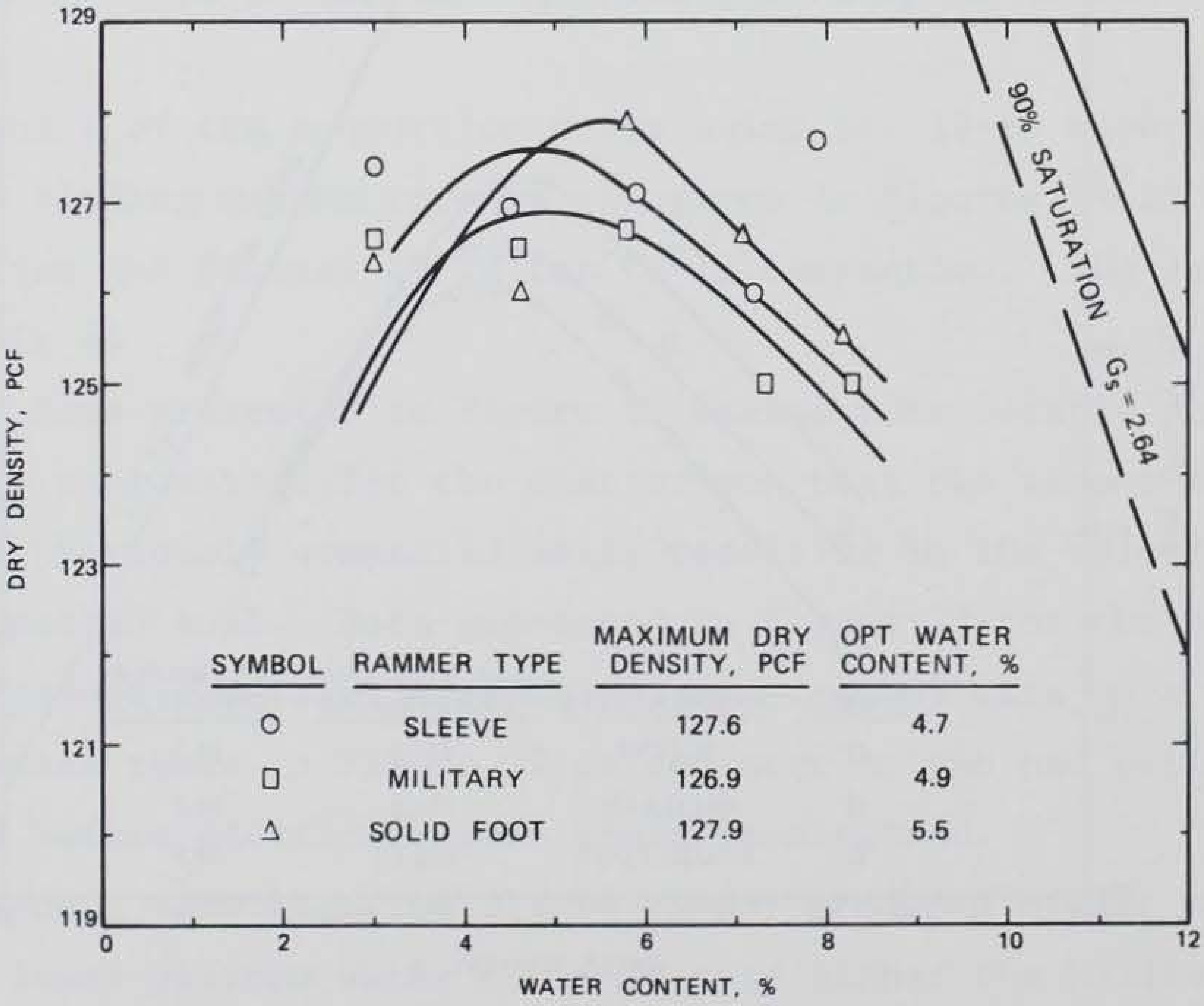


Figure 22. Modified compaction tests on SC soil using existing 10-lb manual rammers

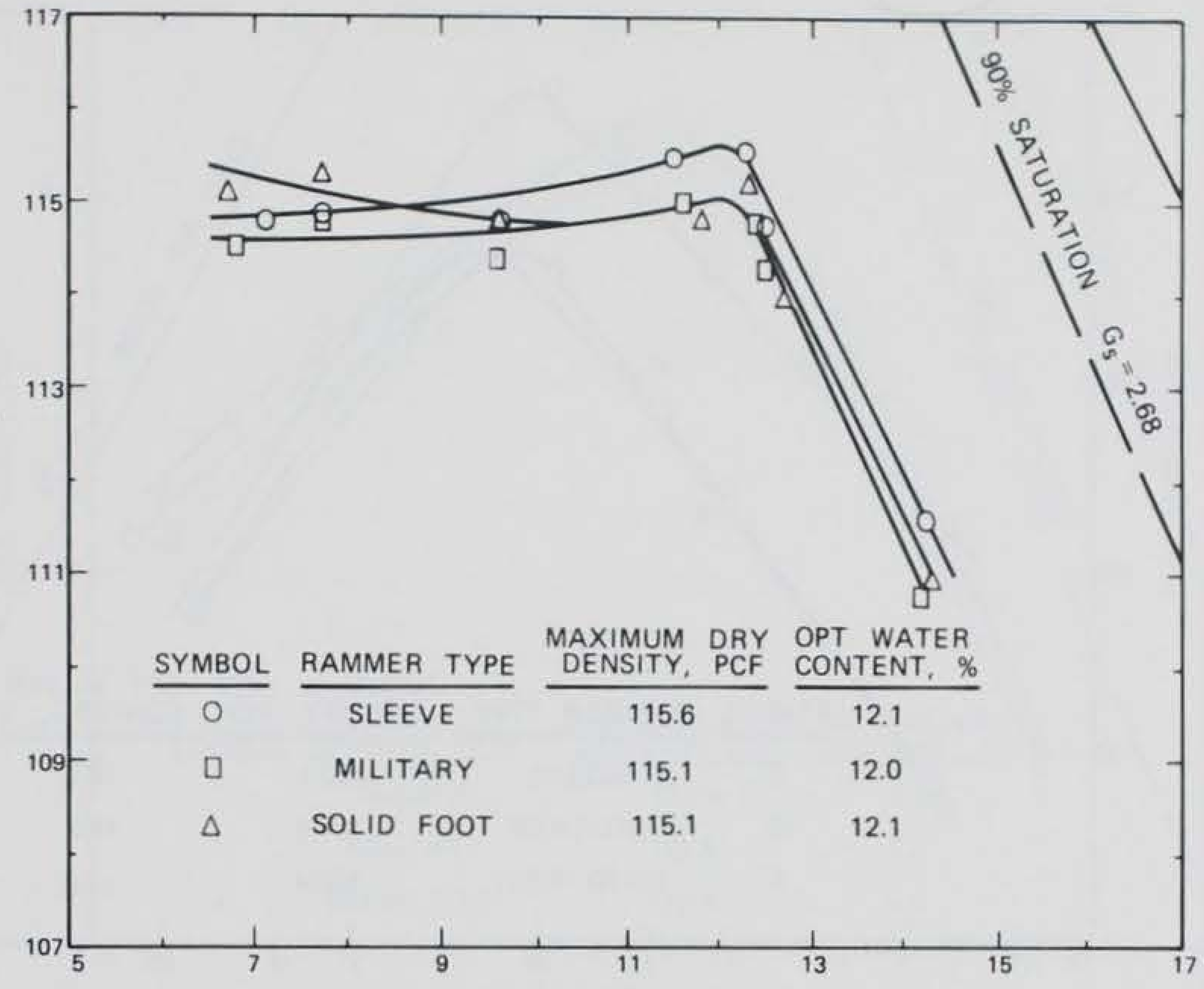


Figure 23. Modified compaction tests on SM soil using existing 10-lb manual rammers

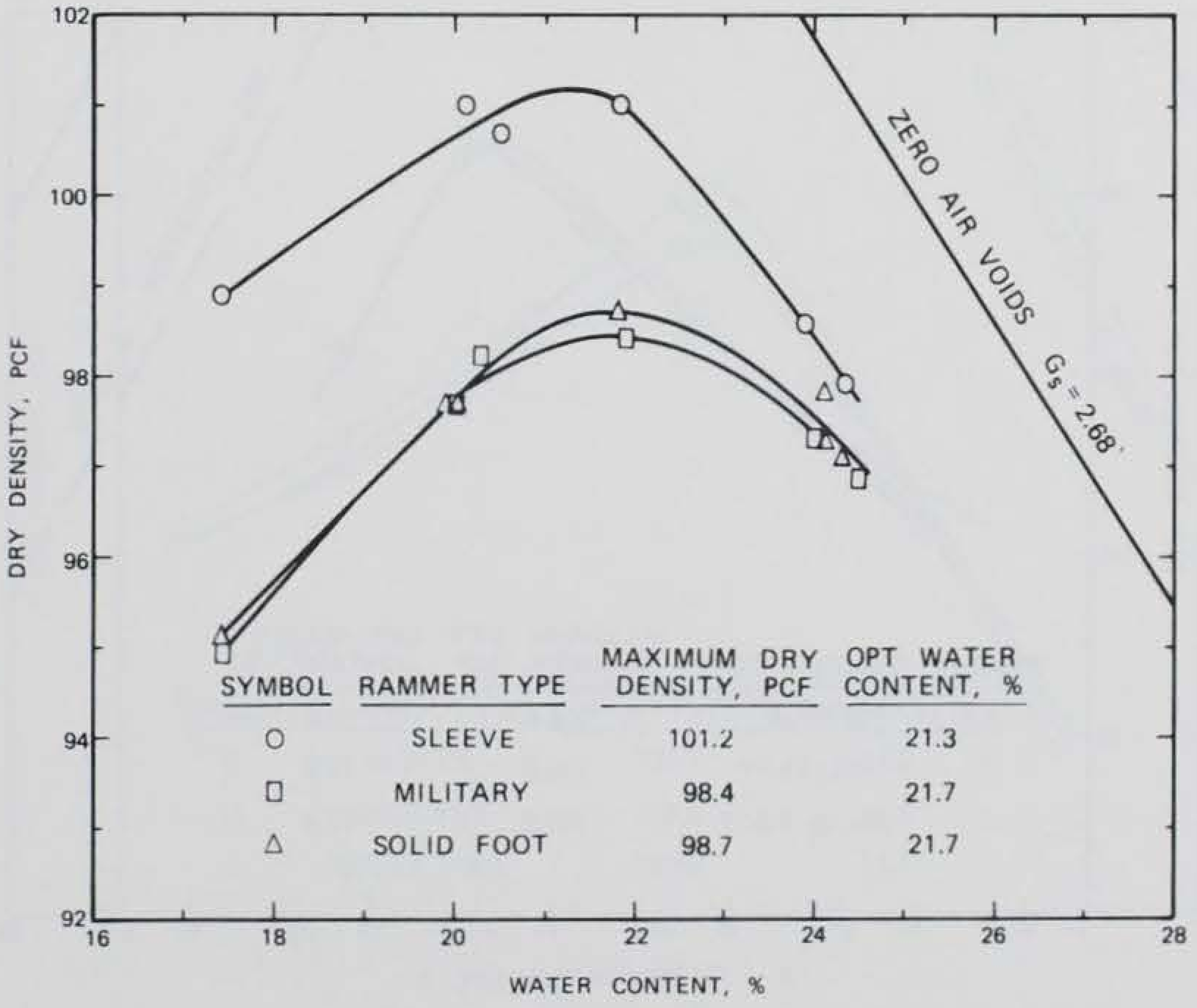


Figure 24. CE-12 compaction tests on CH soil using existing 10-lb manual rammers

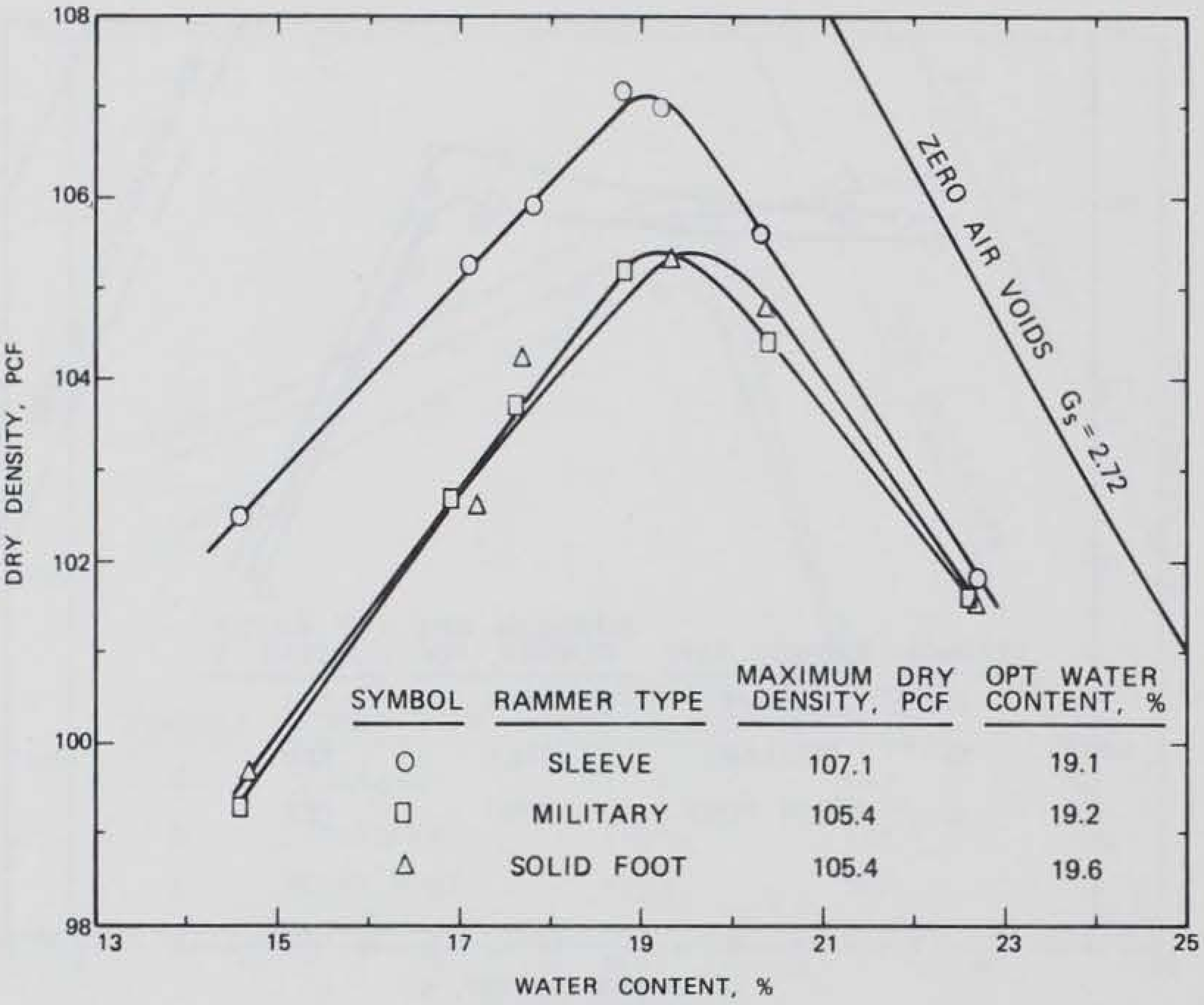


Figure 25. CE-12 compaction tests on CL2 soil using existing 10-lb manual rammers

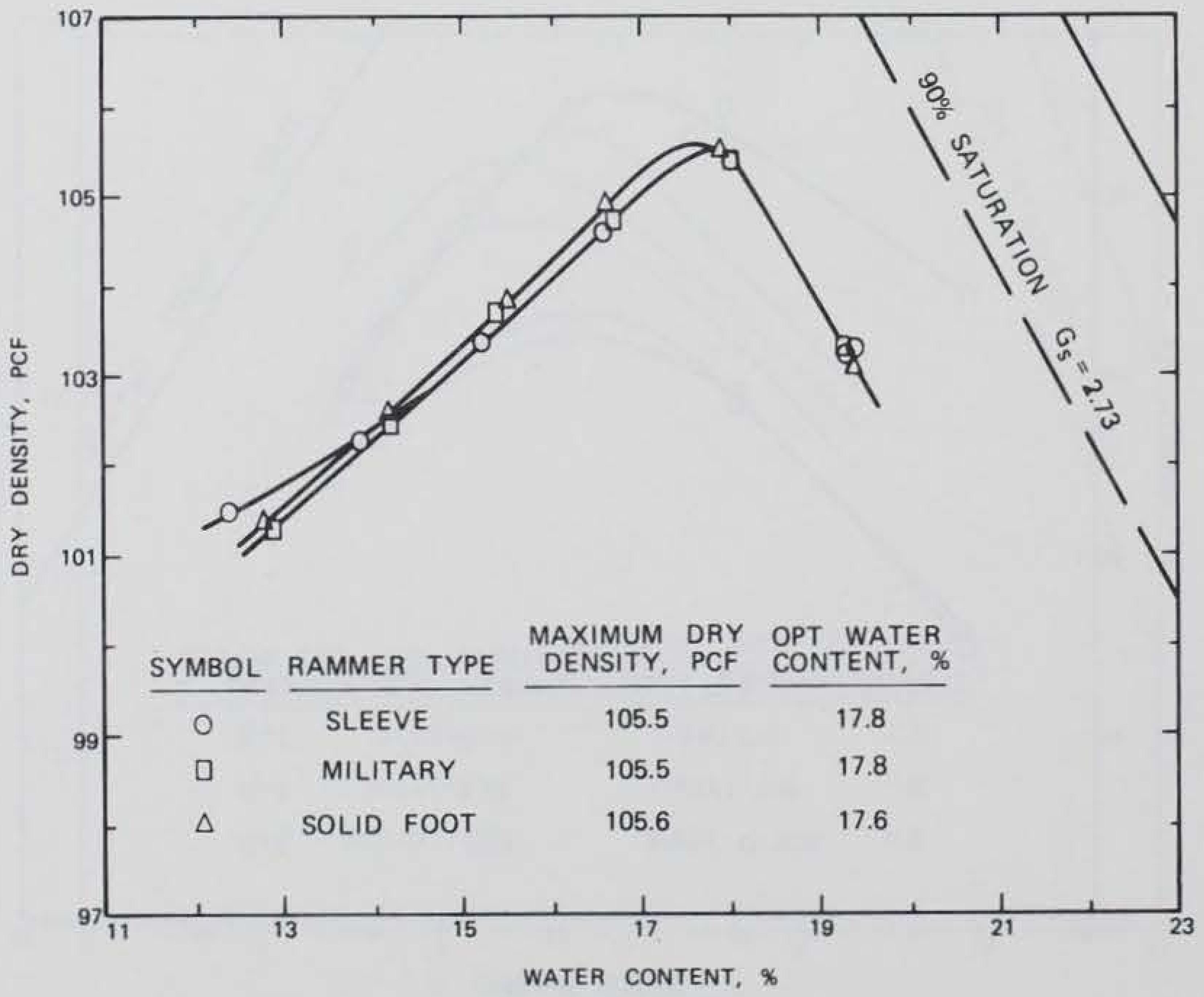


Figure 26. CE-12 compaction tests on CL soil using existing 10-lb manual rammers

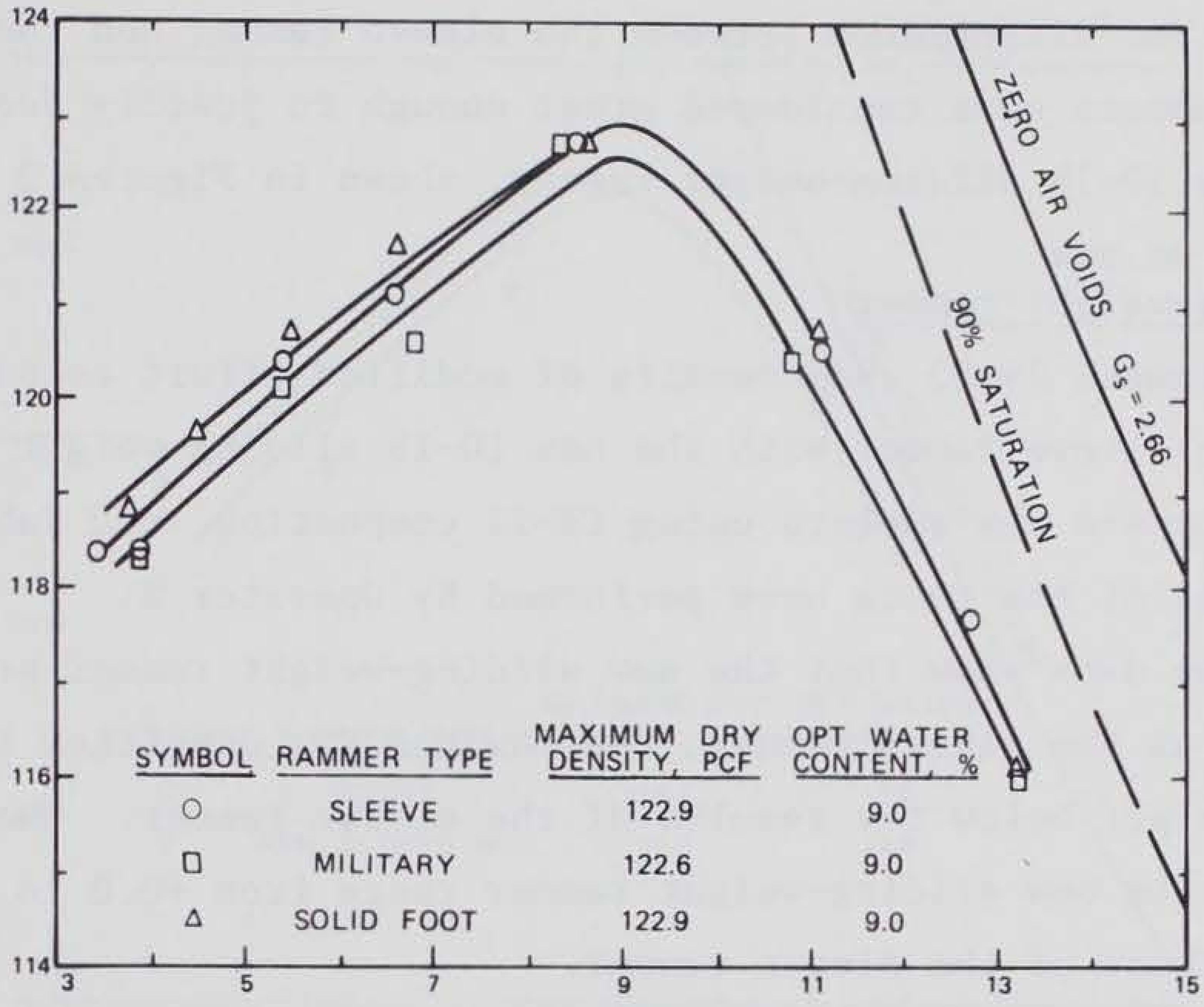


Figure 27. CE-12 compaction tests on SC soil using existing 10-lb manual rammers

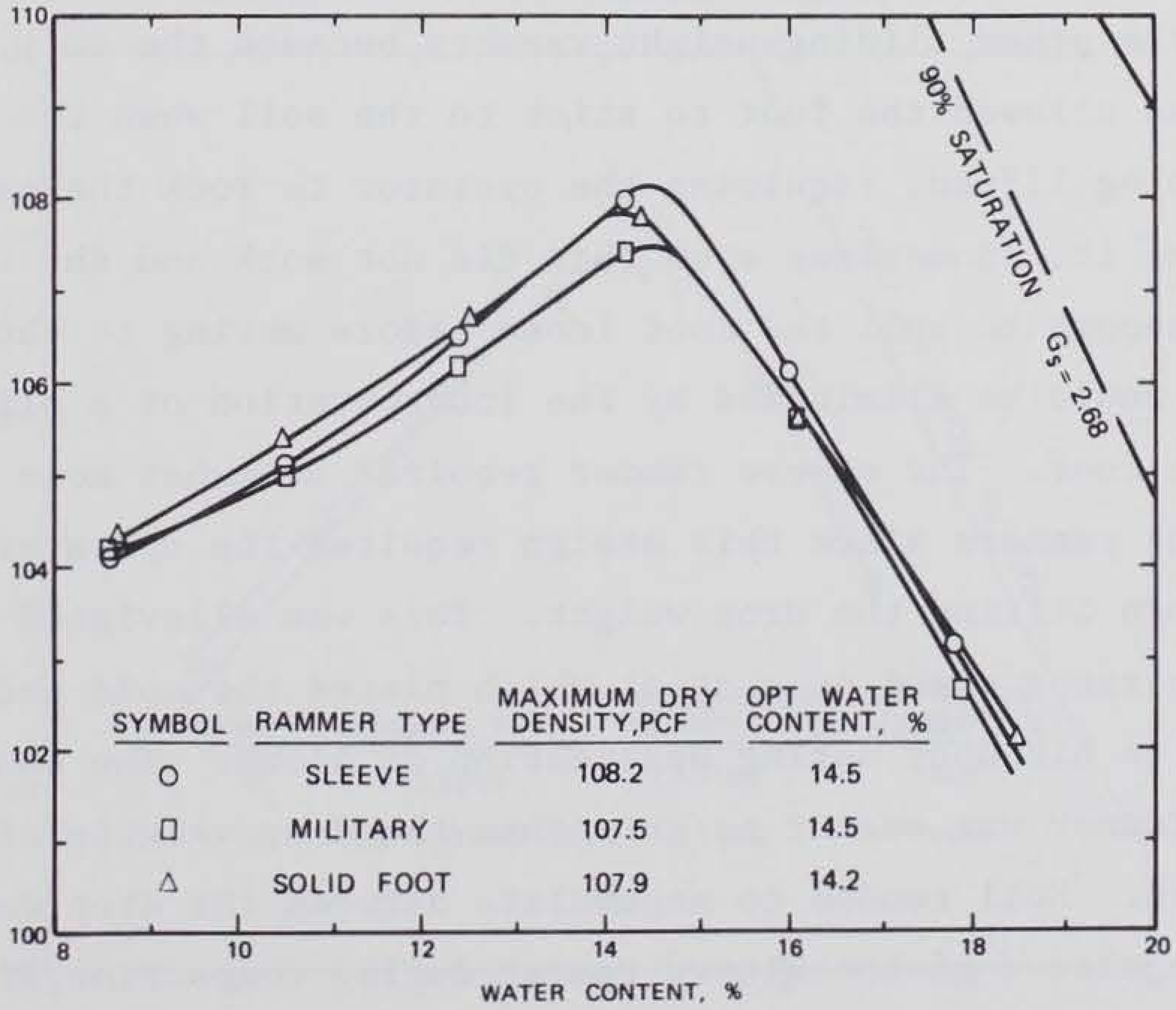


Figure 28. CE-12 compaction tests on SM soil using existing 10-lb manual rammers

differences for the solid foot rammer were 2.8 pcf maximum dry density and 1.7 percentage points optimum water content both on the CH soil using modified compaction. The differences between the sleeve rammer and the Military and solid foot rammers were considered great enough to justify designing and testing a new 10-lb sliding-weight rammer, shown in Figures 3 and 4.

Test results on new 10-lb sliding-weight rammer

63. Figures 29-33 show results of modified effort compaction tests comparing the sleeve rammer with the new 10-lb sliding-weight rammer. Figures 34-38 compare the rammers using CE-12 compaction, and Table 5 summarizes the data. All of the tests were performed by Operator B.

64. The data show that the new sliding-weight rammer produces about the same results as the sleeve rammer, the maximum dry densities being 0.2 pcf above the 0.6 pcf below the results of the sleeve rammer. The optimum water contents for the new sliding-weight rammer range from +0.8 to -0.2 percentage points from those of the sleeve rammer.

Operation of rammers

65. Operational ease of the Military and solid foot sliding-weight rammers was about the same. The new sliding-weight rammer was more difficult to use than the other sliding-weight rammers because the soft spring in the foot sometimes allowed the foot to stick to the soil when the rest of the rammer was being lifted, requiring the operator to rock the rammer slightly before lifting it. Sometimes even this did not work and the rammer had to be lifted high enough to pull the foot loose before moving to the next position. This problem would be eliminated by the incorporation of a slightly stiffer spring in the foot. The sleeve rammer required somewhat more effort than the sliding-weight rammers since this design required the operator to raise his arm higher when lifting the drop weight. This was alleviated to a degree by having the operator stand on a stool which placed the mold and rammer lower with respect to his body during application of blows. The shaft of the sleeve-type rammer was easier to grip than the drop weights of the sliding-weight rammers. Soil tended to accumulate between the drop weight and the inside of the sleeve of the sleeve rammer during compaction of the wettest points of the SC soil. This resulted in slight binding which necessitated twisting the drop weight as it was raised in preparation for the next blow.

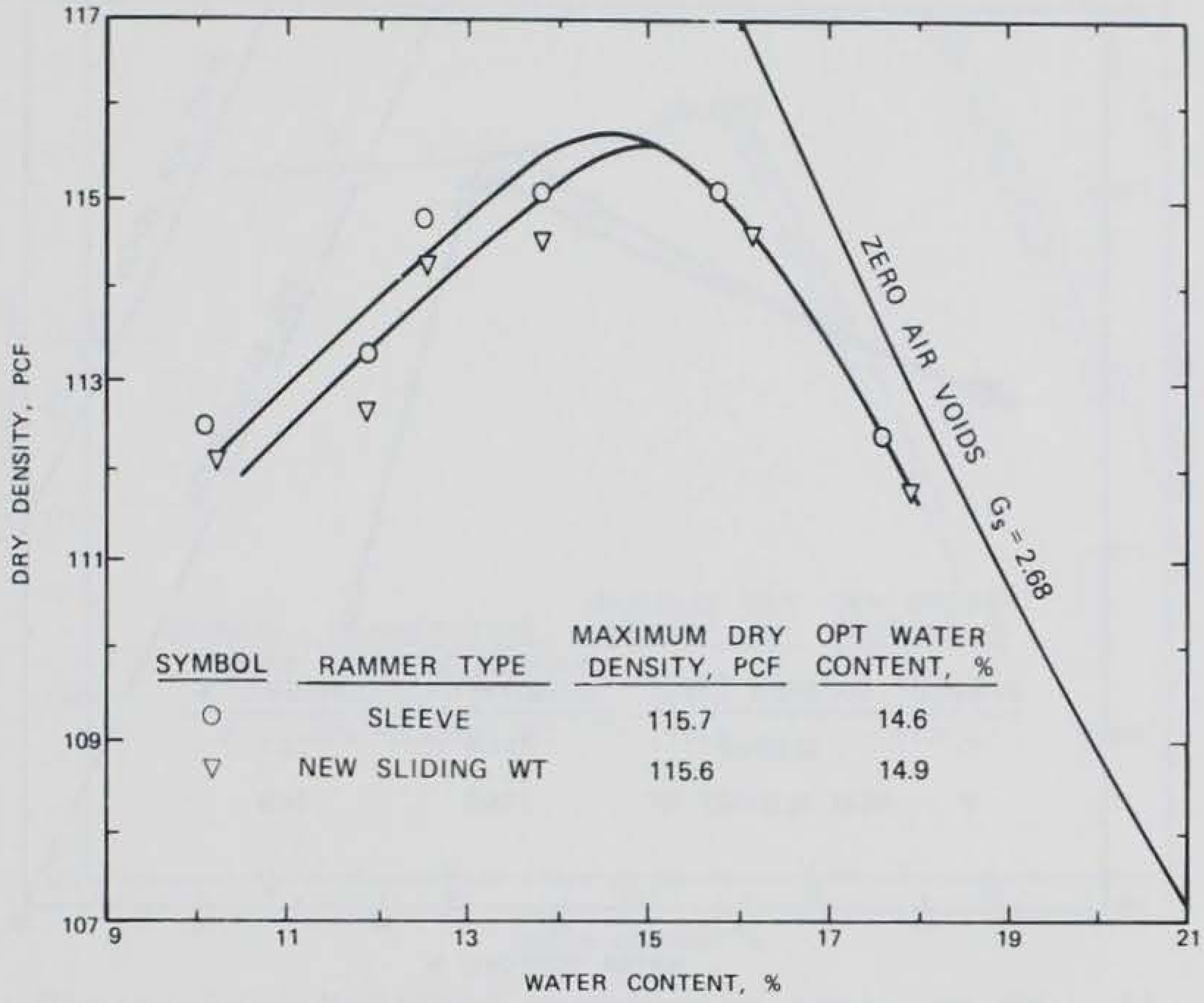


Figure 29. Modified compaction tests on CH soil using new 10-lb manual rammer

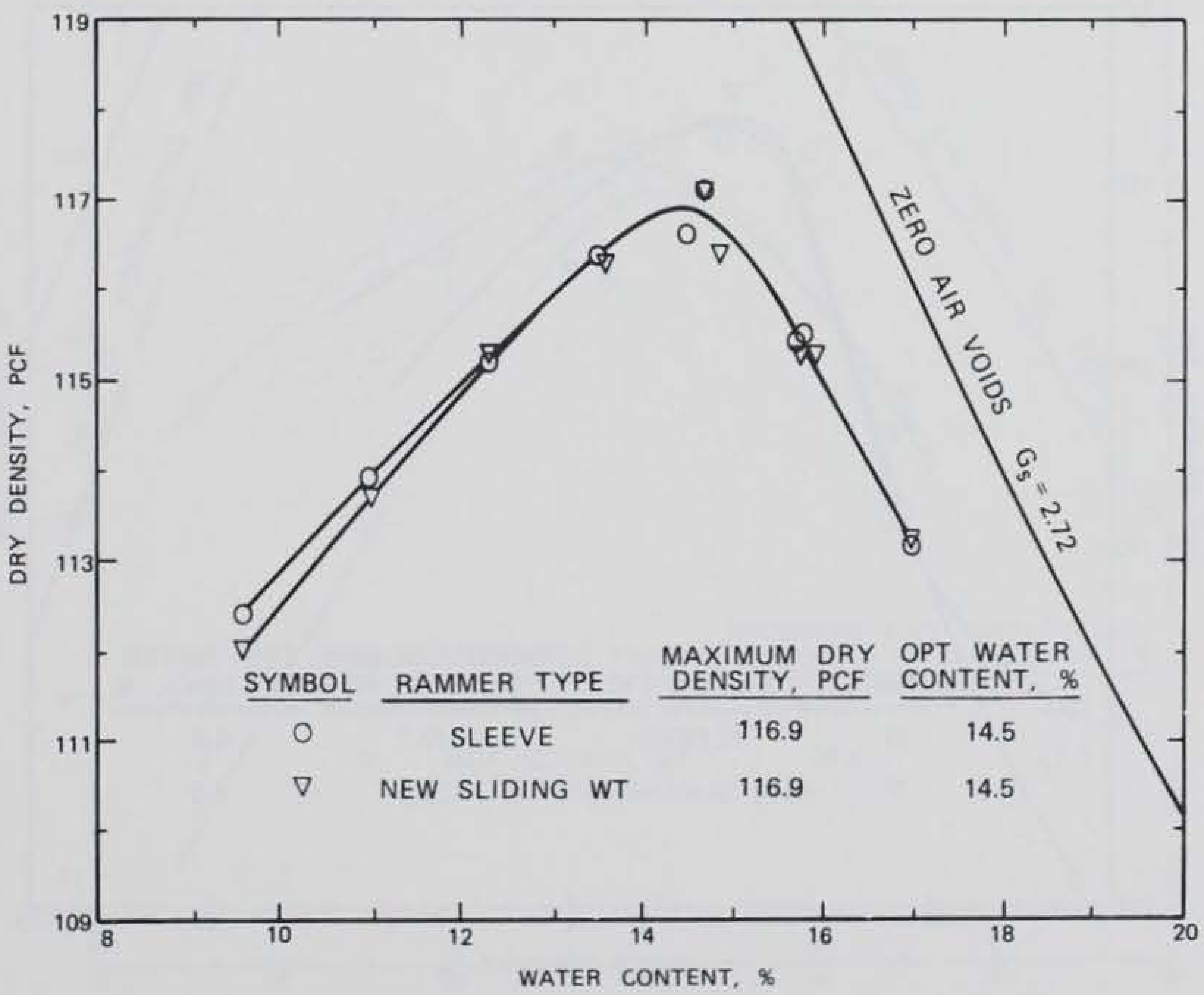


Figure 30. Modified compaction tests on CL2 soil using new 10-lb manual rammer

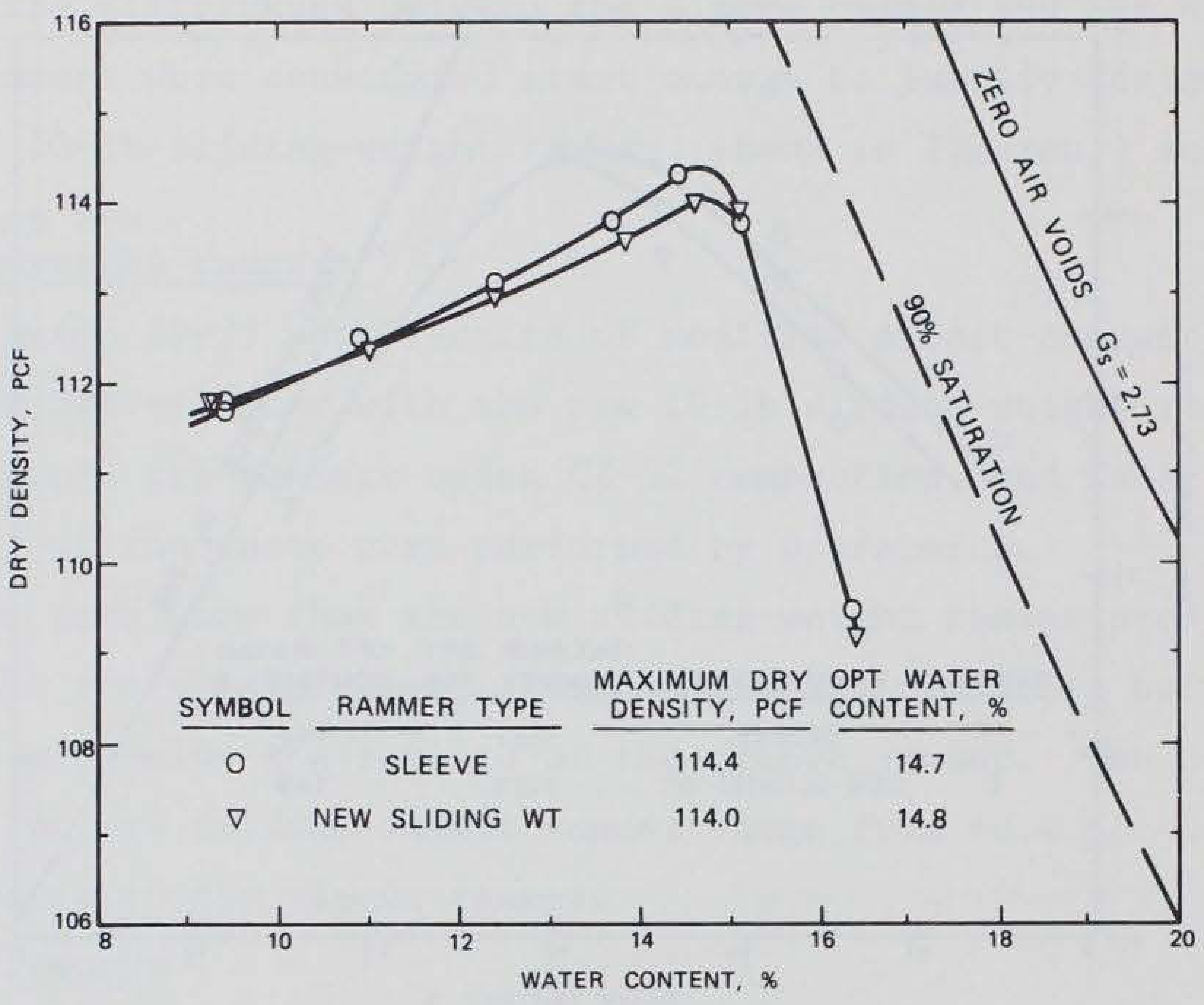


Figure 31. Modified compaction tests on CL soil using new 10-lb manual rammer

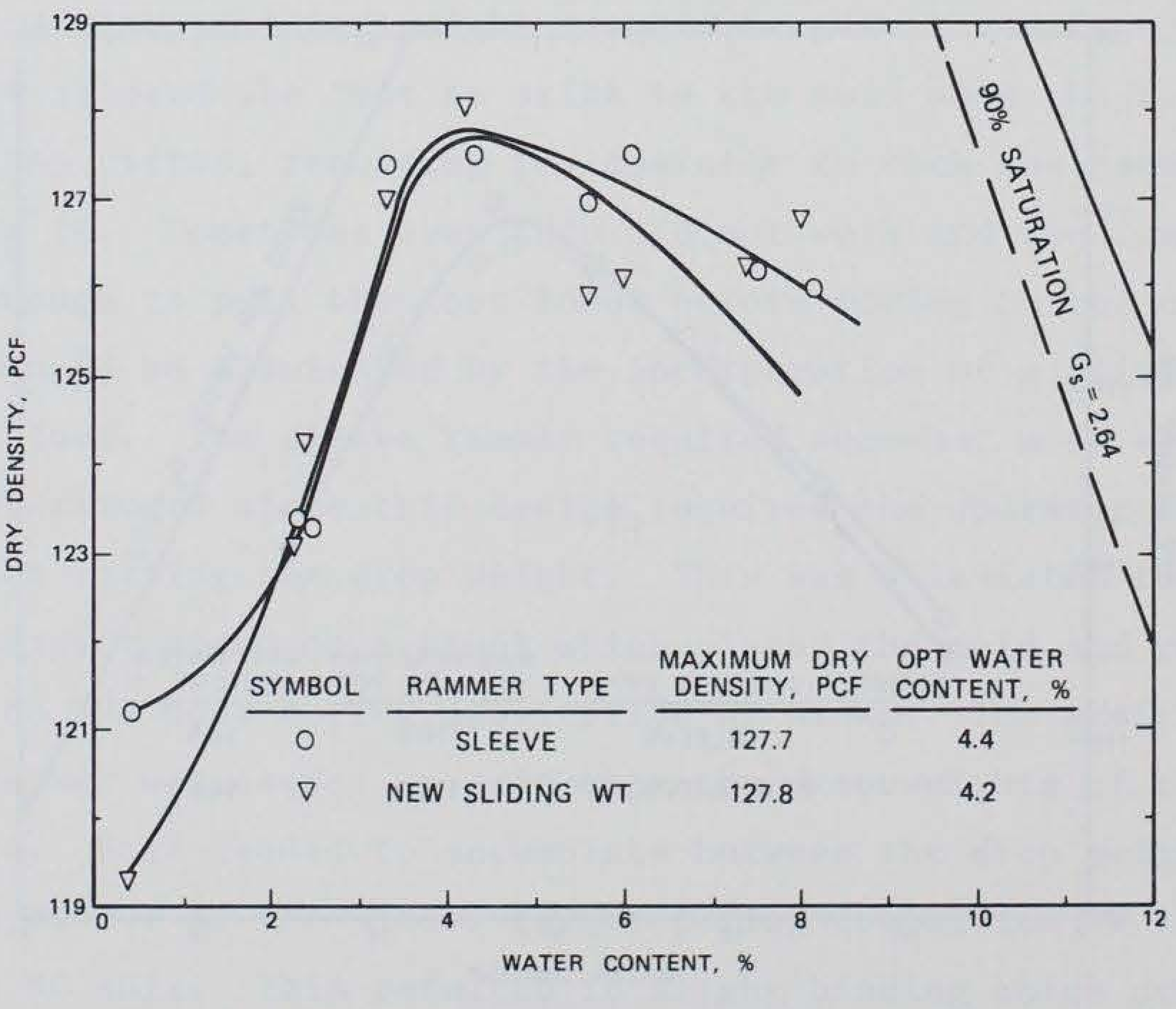


Figure 32. Modified compaction tests on SC soil using new 10-lb manual rammer

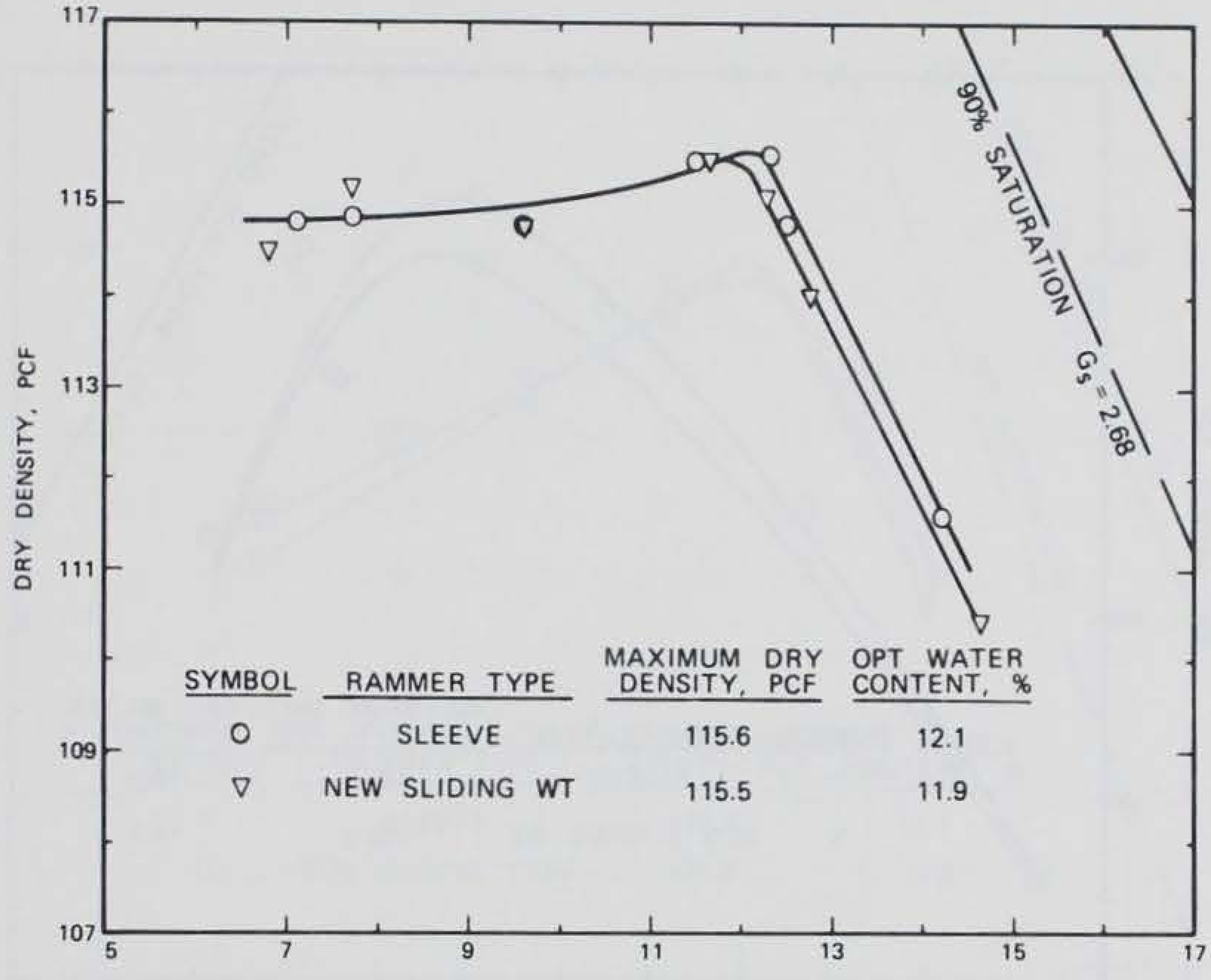


Figure 33. Modified compaction tests on SM soil using new 10-lb manual rammer

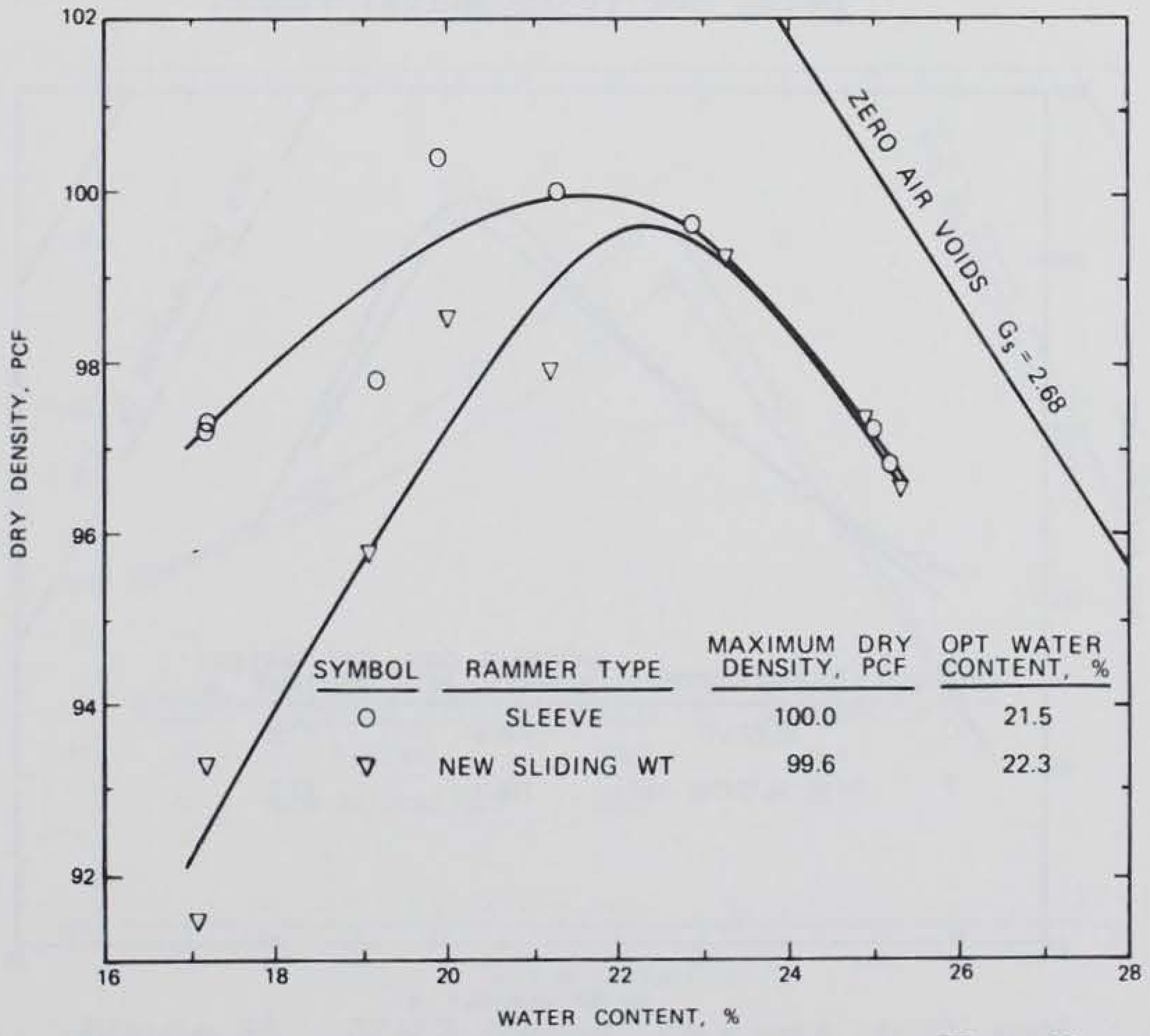


Figure 34. CE-12 compaction tests on CH soil using new 10-lb manual rammer

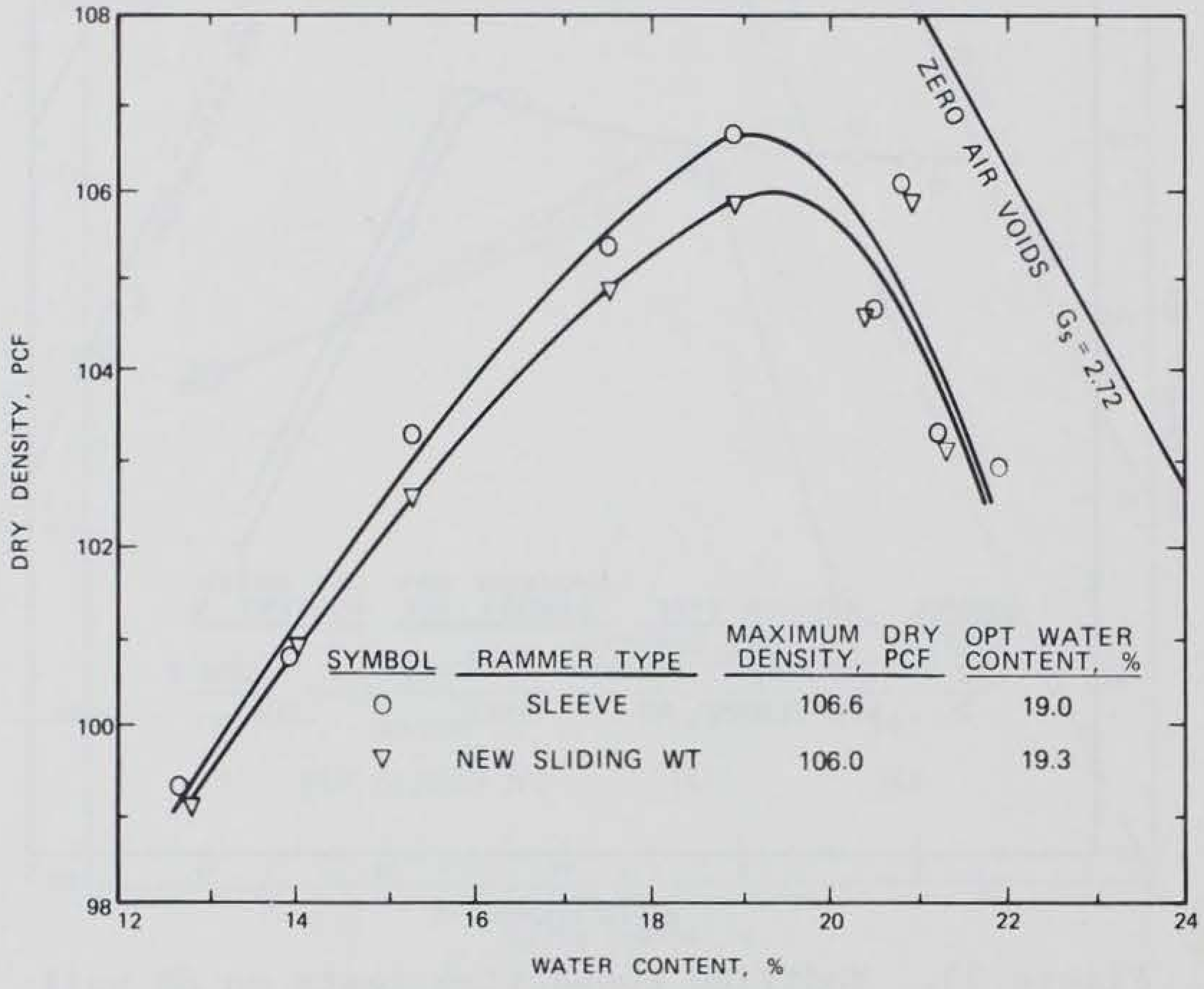


Figure 35. CE-12 compaction tests on CL2 soil using new 10-lb manual rammer

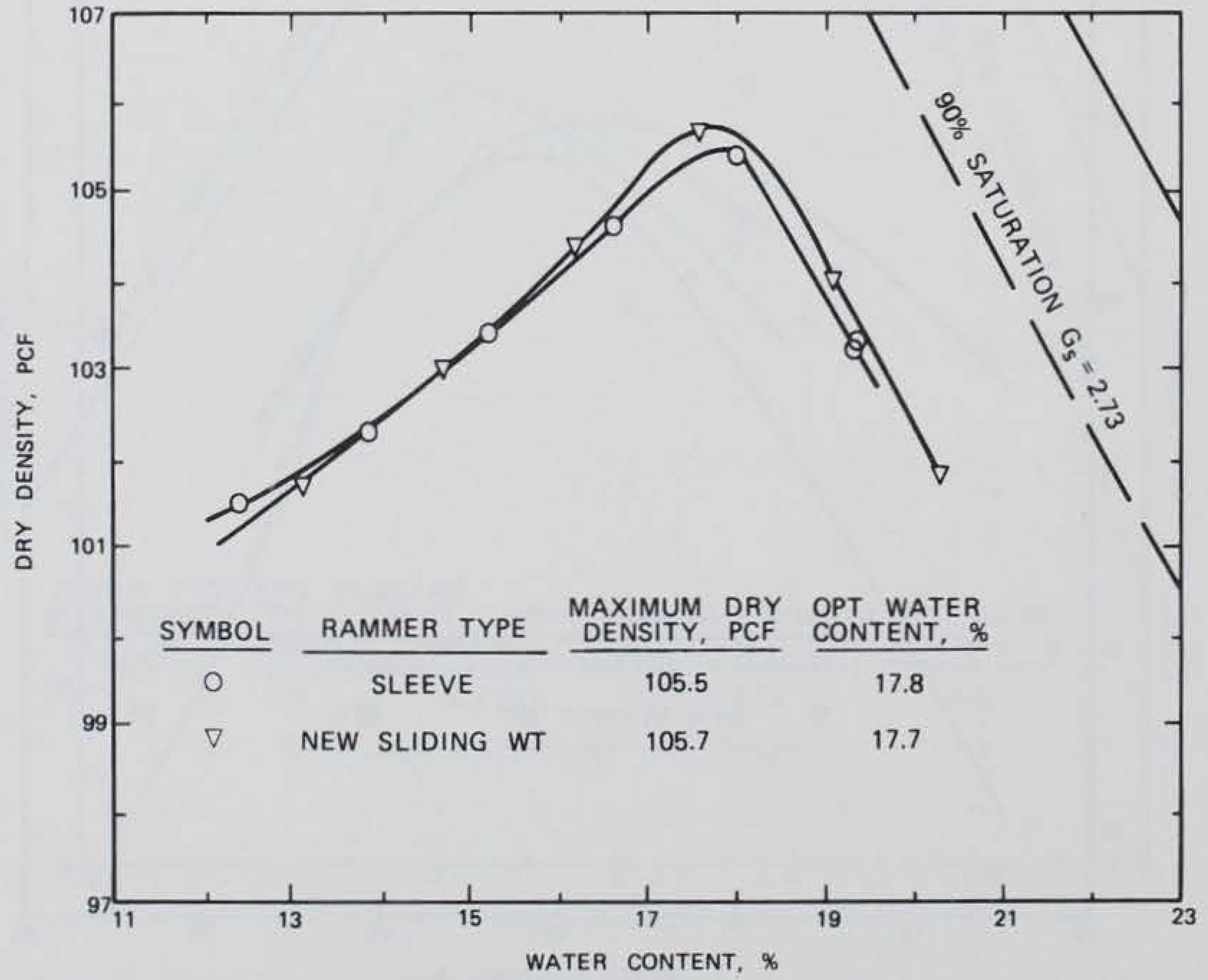


Figure 36. CE-12 compaction tests on CL soil using new 10-lb manual rammer

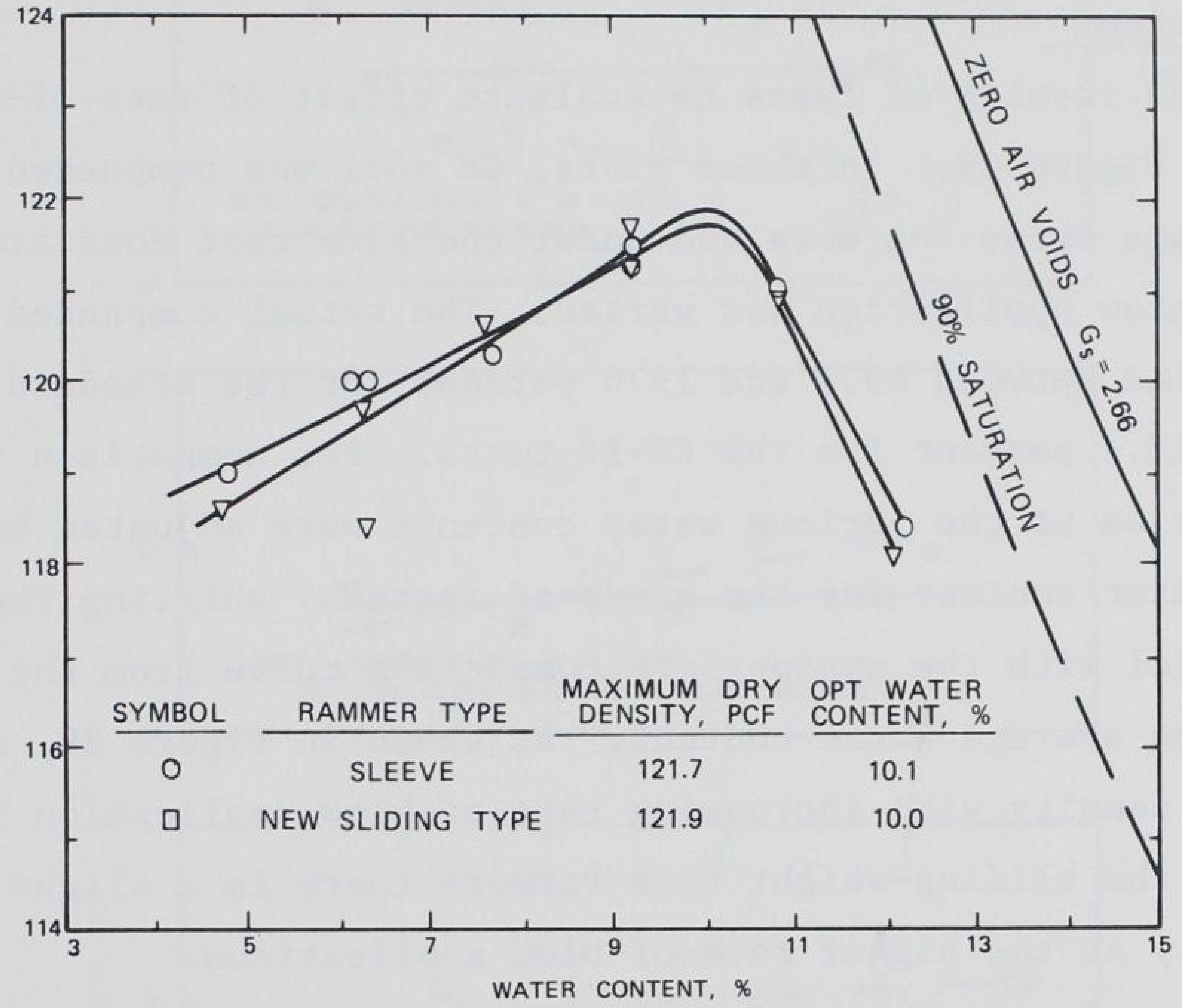


Figure 37. CE-12 compaction tests on SC soil using new 10-lb manual rammer

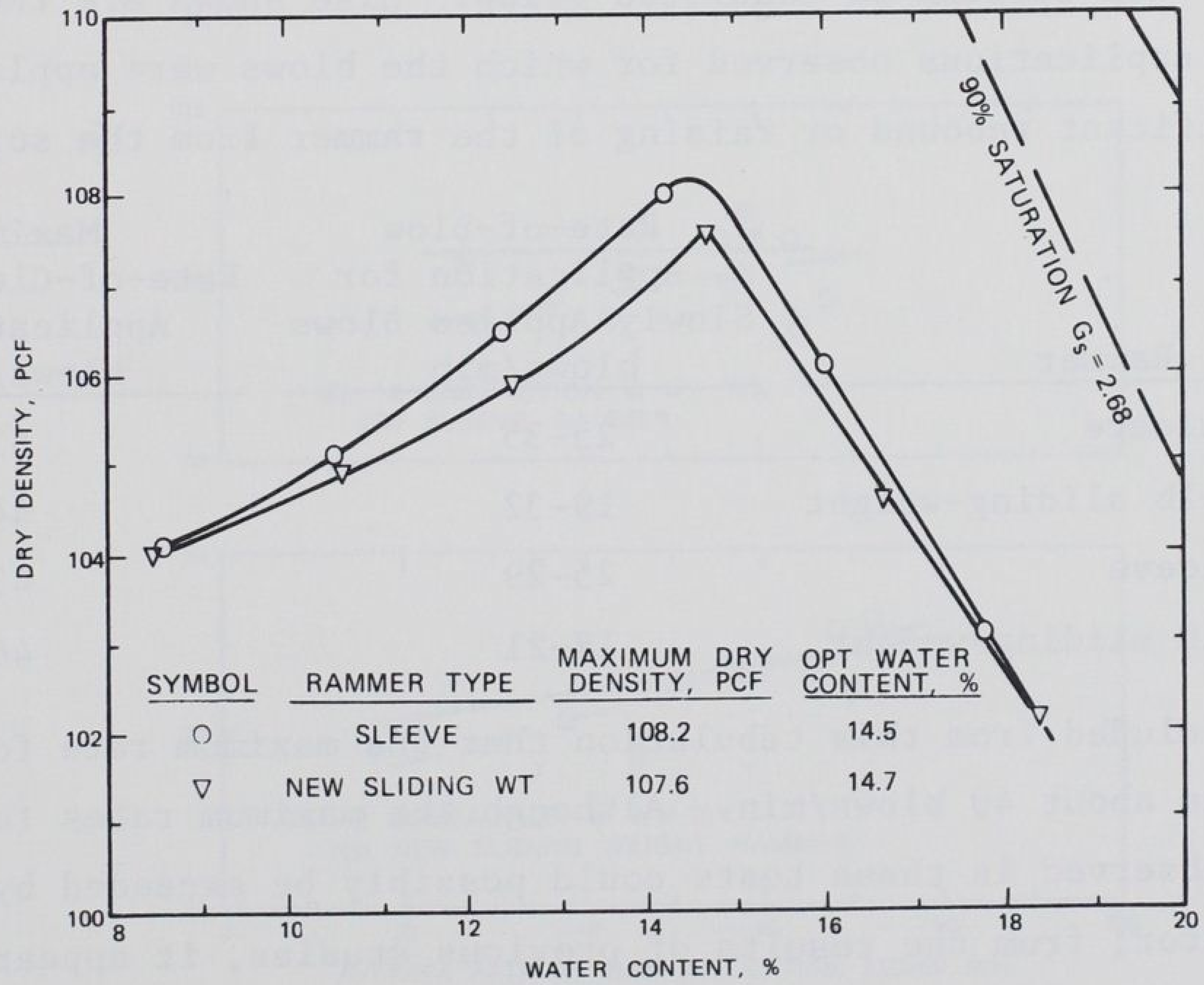


Figure 38. CE-12 compaction tests on SM soil using new 10-lb manual rammer

Effect of rate-of-blow application

66. The results of tests to evaluate effect of rate-of-blow application are shown in Figure 39. In these plots, CH soil was compacted at approximately the same water contents and under the same test conditions except that the rate-of-blow application was varied. The actual compacted specimen water contents varied between 19.1 and 19.6 percent for the standard effort tests and 17.6 to 18.4 percent for the CE-12 tests. For comparison purposes each of the densities at the various water contents were adjusted to a density at an average water content for the group of tests by shifting the density along a line parallel with the appropriate compaction curve from the actual water content to the average water content. As shown in Figure 39, no significant trend in dry density with increasing rate-of-blow application is evident, although for the sliding-weight type rammers there is a slight increase (1 pcf) in dry density at the higher rate-of-blow applications.

67. The range in rate-of-blow application determined during the rammer verification tests and during the slow rate-of-blow application trials for this phase of testing is tabulated below. Also shown are the fastest rate-of-blow applications observed for which the blows were applied cleanly without significant rebound or raising of the rammer from the soil surface.

Rammer	Rate-of-Blow Application for Slowly Applied Blows blows/min	Maximum Rate-of-Clean-Blow Application blows/min
5.5-lb sleeve	25-35	53
New 5.5-lb sliding-weight	19-32	44
10-lb sleeve	25-29	43
New 10-lb sliding-weight	17-21	46

It can be concluded from this tabulation that the maximum rate for clean blow application is about 40 blows/min. Although the maximum rates for clean blow application observed in these tests could possibly be exceeded by a highly skilled operator; from the results of previous studies, it appears that the tendency of many operators to develop a rhythm which enables them to apply blows at a more rapid rate than shown above is a source of variation in soil densities between operators. Failure to apply clean blows using the manual

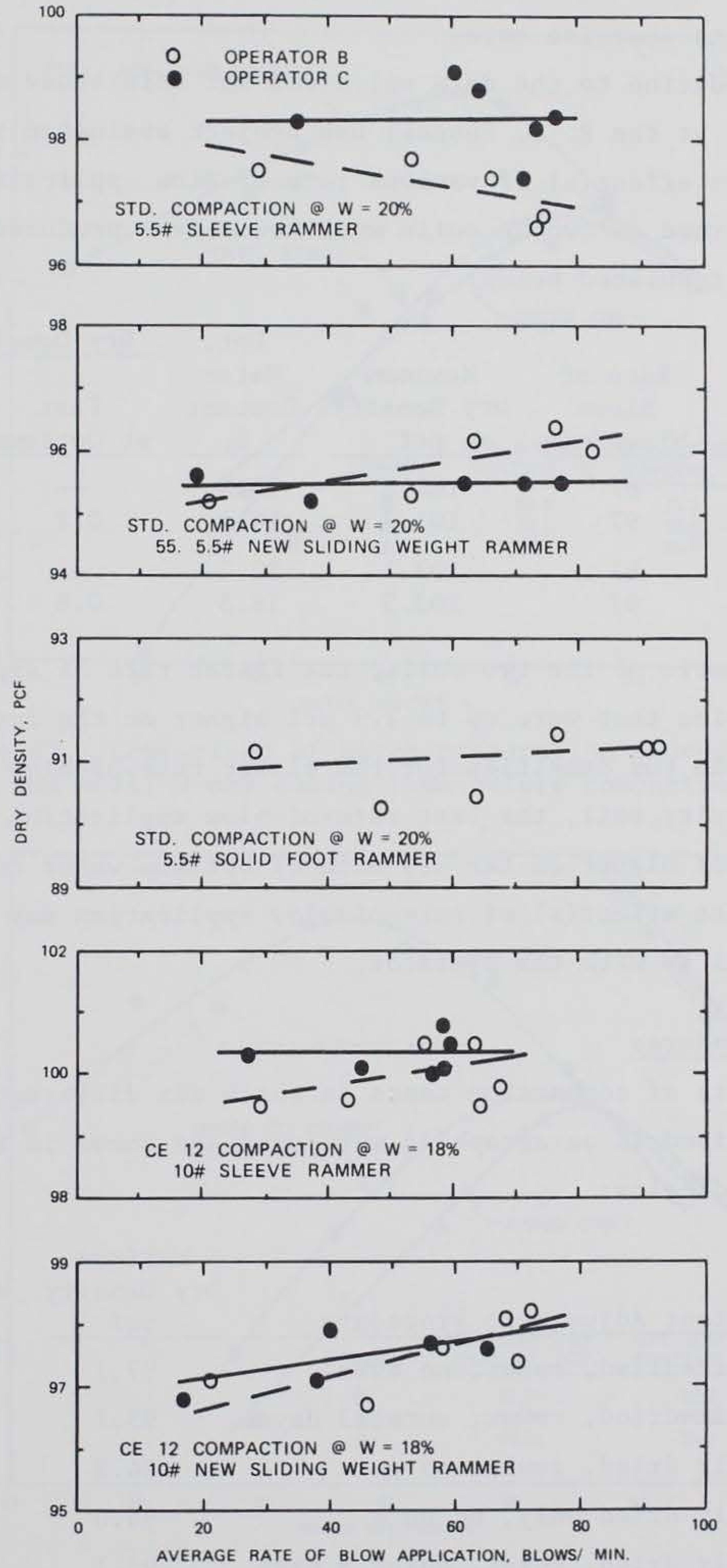


Figure 39. Effect of rate-of-blow application on densities of CH soil using manual rammers

rammers could, of course, occur at any rate-of-blow application if the operator failed to exercise care.

68. In addition to the data collected for this study at WES, the materials laboratory at the R. B. Russell Dam project evaluated the new sliding-weight rammer for effect(s) of various rate-of-blow applications. Compaction tests were performed on two ML soils with two curves produced on each soil. The results are tabulated below.

Soil	Rate of Blows blows/min	Maximum Dry Density pcf	Opt. Water Content %	Dry Density Difference Fast at Optimum	Dry Density Difference Slow at Optimum - 3 Percent
Lower	67	104.8	18.8	--	--
Plasticity ML	97	105.7	18.5	0.9	2.9
Higher	67	103.1	20.2	--	--
Plasticity ML	97	103.9	18.5	0.8	1.3

For the more plastic of the two soils, the faster rate of application produced dry densities that were up to 2.9 pcf higher on the dry side of optimum water content than the densities for the slower rate-of-blow application. For the lower plasticity soil, the fast rate-of-blow application produced densities up to 1.3 pcf higher on the dry side of optimum water content. This indicates that the effect(s) of rate-of-blow application may vary with the soil type as well as with the operator.

Evaluation of soil preparation procedures

69. Results of compaction tests in which six different preparation procedures described in paragraph 42 were used are shown in Figures 40-41 and are tabulated below:

Water Content Adjustment Procedure	Maximum Dry Density pcf	Optimum Water Content percent
Soil fully air-dried, rewet, no cure	97.1	22.5
Soil fully air-dried, rewet, cured 3 days	95.1	24.2
Soil partially dried, rewet, no cure	94.2	25.5
Soil partially dried only, no cure	94.0	26.0
Soil partially dried, rewet, cured 3 days	93.1	25.5
Soil partially dried only, cured 3 days	93.2	26.1

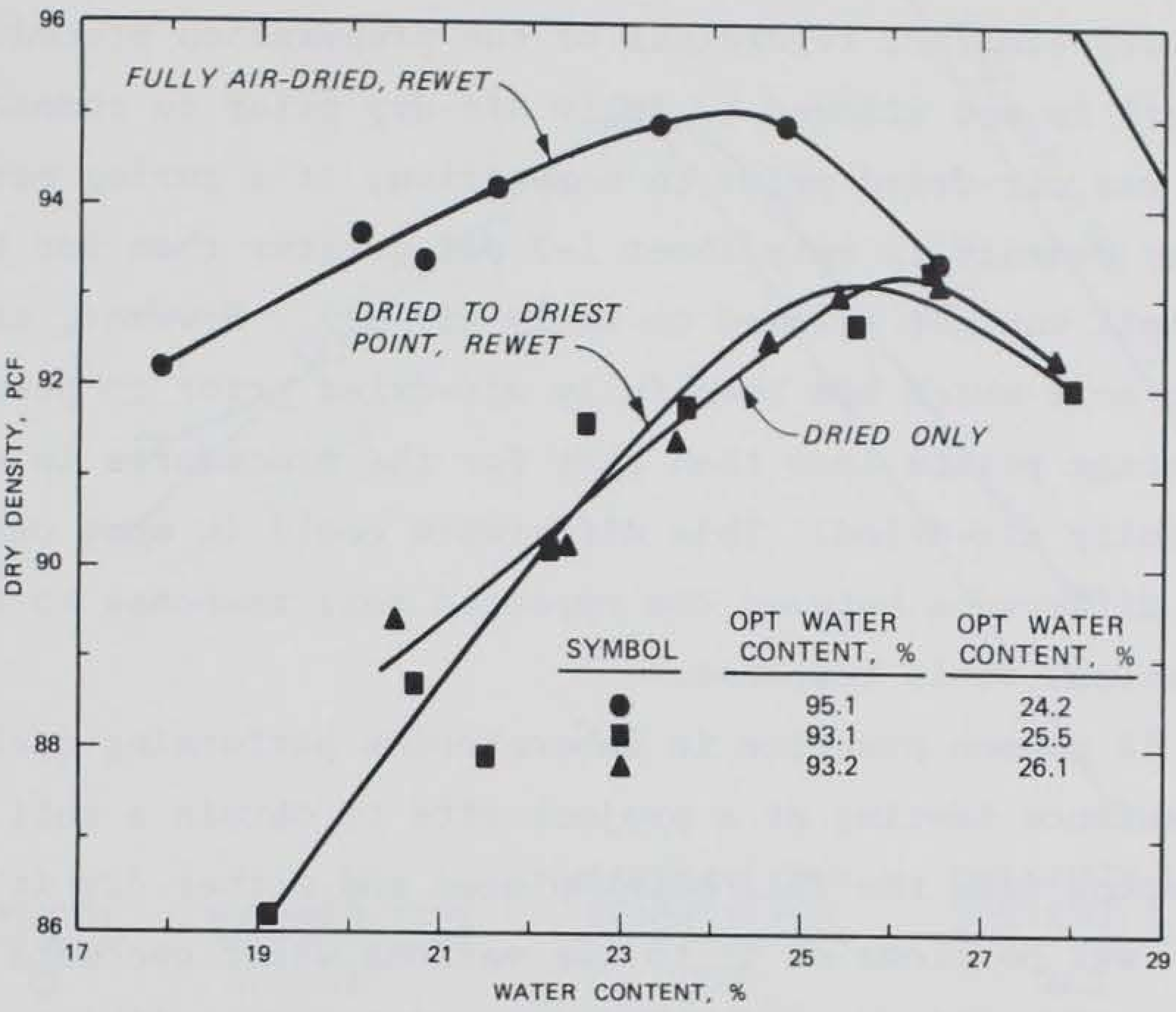


Figure 40. Comparison of batch preparation procedures on CH2 soil; 3-day curing time before compaction

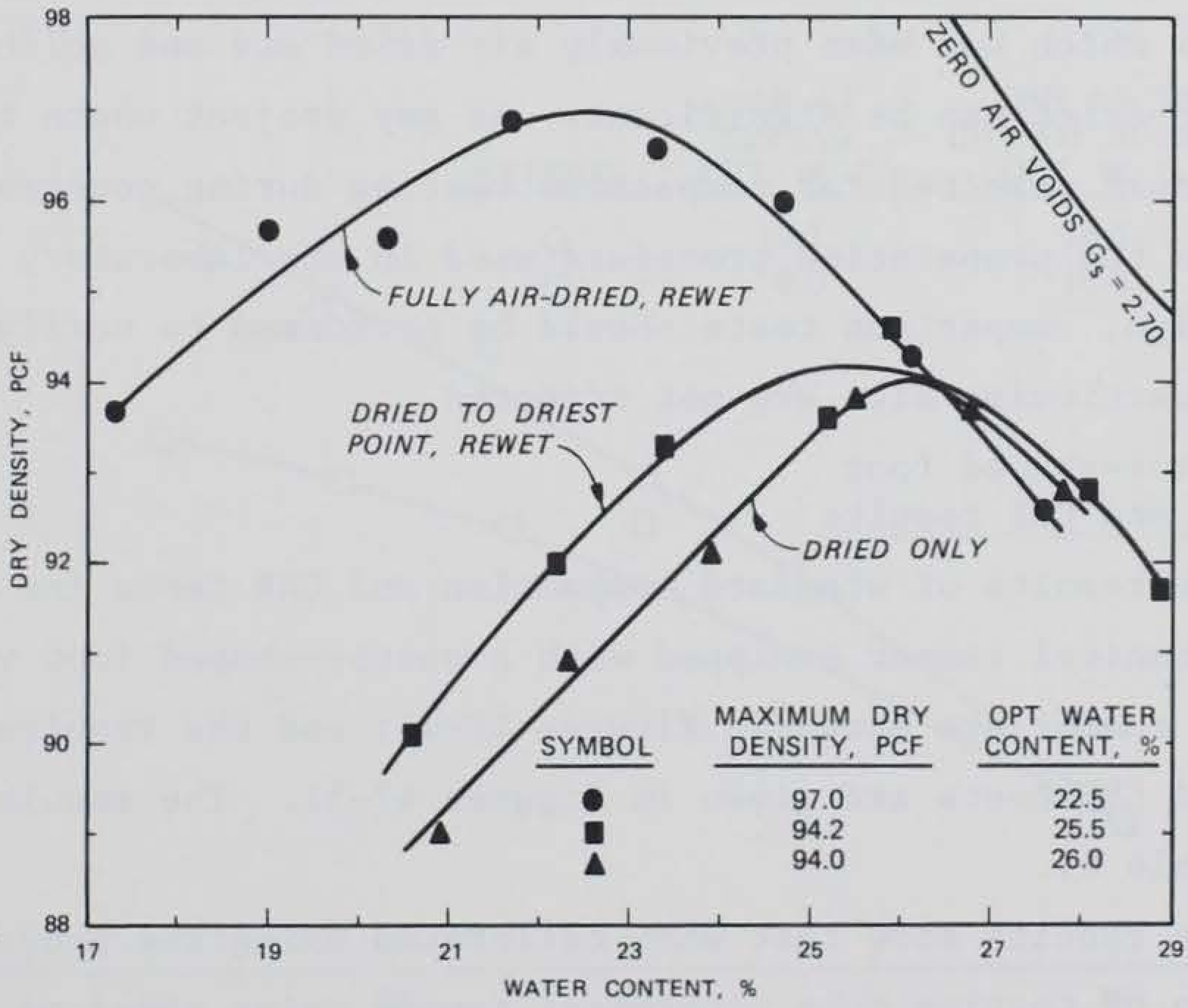


Figure 41. Comparison of batch preparation procedures on CH2 soil; no curing time before compaction

70. The tabulation shows that maximum dry densities and optimum water contents are very similar, regardless of the preparation procedure used as long as the soil is not allowed to fully air-dry prior to compaction. Even when the soil was air-dried prior to compaction, if a curing period is allowed, the maximum dry density is only about 1-2 pcf greater than for the procedures in which the soil was not allowed to fully air-dry. However, the optimum water content of the soil which had been fully air-dried prior to preparation was 1.3-1.8 percentage points less than that for the procedures in which the soil was not fully air-dried. This difference could in some cases result in a significant difference between the expected soil response to field compaction and the actual field response.

71. It is common practice in laboratories performing quality control or quality assurance testing at a project site to obtain a soil sample for compaction testing from the fill being placed and either dry it at room temperature or wet portions of it to the various water contents needed to make a complete compaction curve. This material is usually not cured between water content adjustment and compaction. From the testing performed, it is evident that at least for some soils, the difference in compaction results between a soil which has been previously air-dried and one which has not been previously air-dried can be significant. At any project where the soil preparation procedure selected for compaction testing during construction is different from the preparation procedure used in the laboratory compaction tests for design, comparison tests should be performed to verify that the soils at the particular site are not affected.

Effect of sector-shaped foot on compaction and CBR results

72. The results of standard compaction and CBR tests for the five soils using the mechanical rammer equipped with a sector-shaped foot versus the manual sleeve rammer are shown in Figures 42-46; and the results for modified compaction and CBR tests are given in Figures 47-51. The results are summarized in Table 6.

73. The results show that when calibrated using the procedure described for this phase of testing, the mechanical rammer using standard compaction effort produced maximum dry densities that averaged less than 0.3 pcf higher than the average of those produced by the manual rammer and optimum water contents that averaged 0.2 percentage points lower. However, the unsoaked

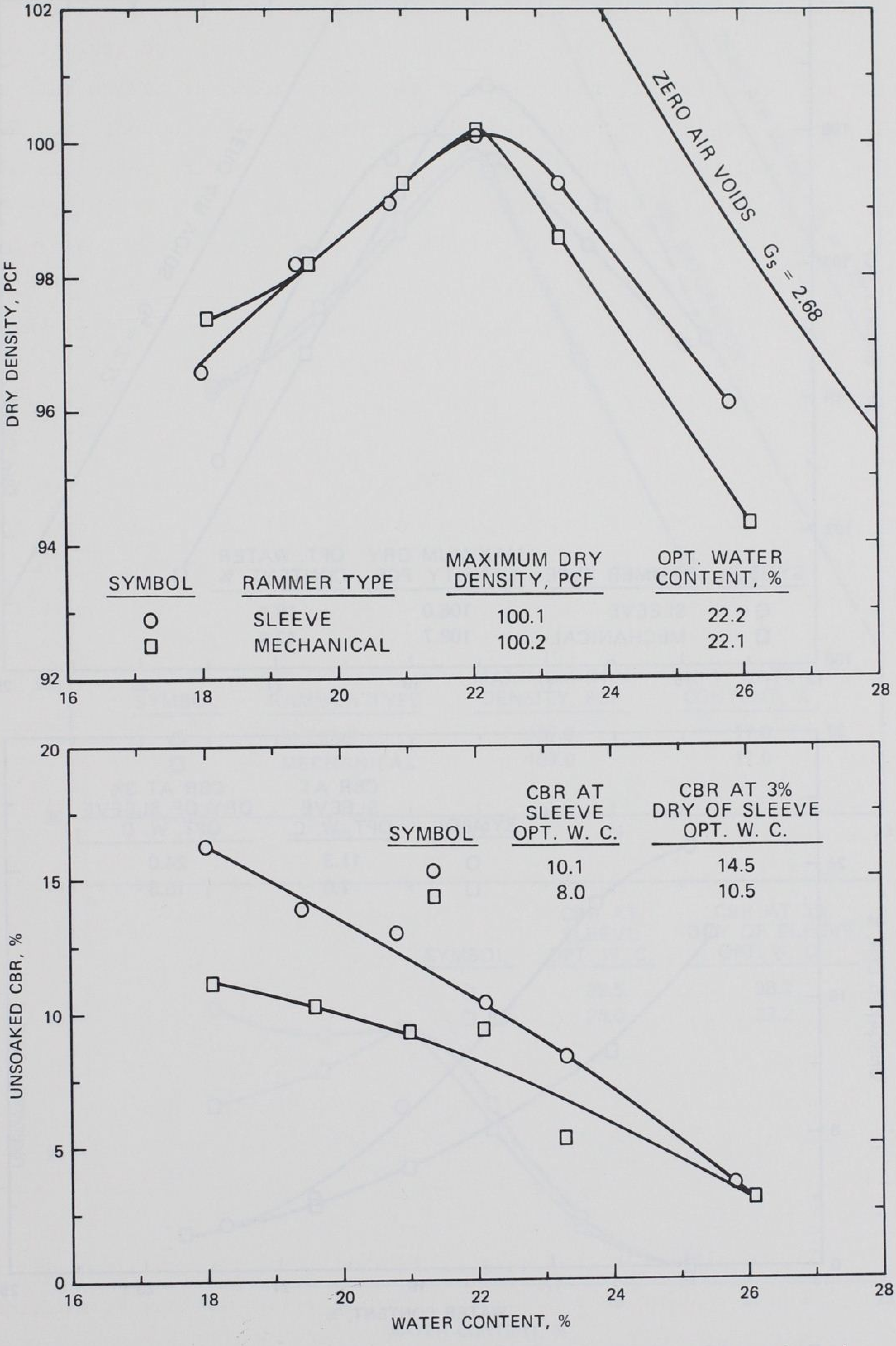


Figure 42. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; standard compaction and CBR tests on CH soil

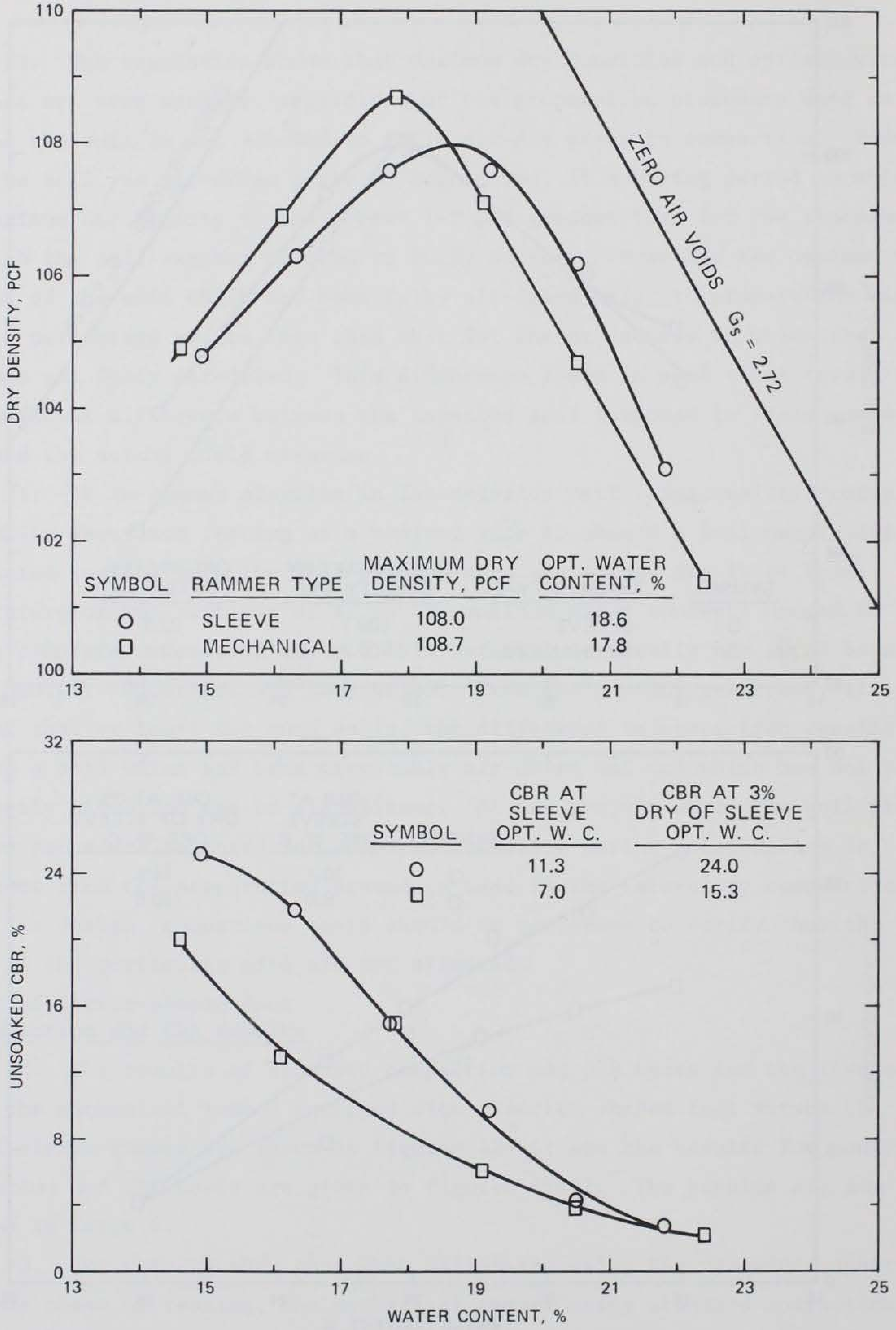


Figure 43. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; standard compaction and CBR tests on CL2 soil

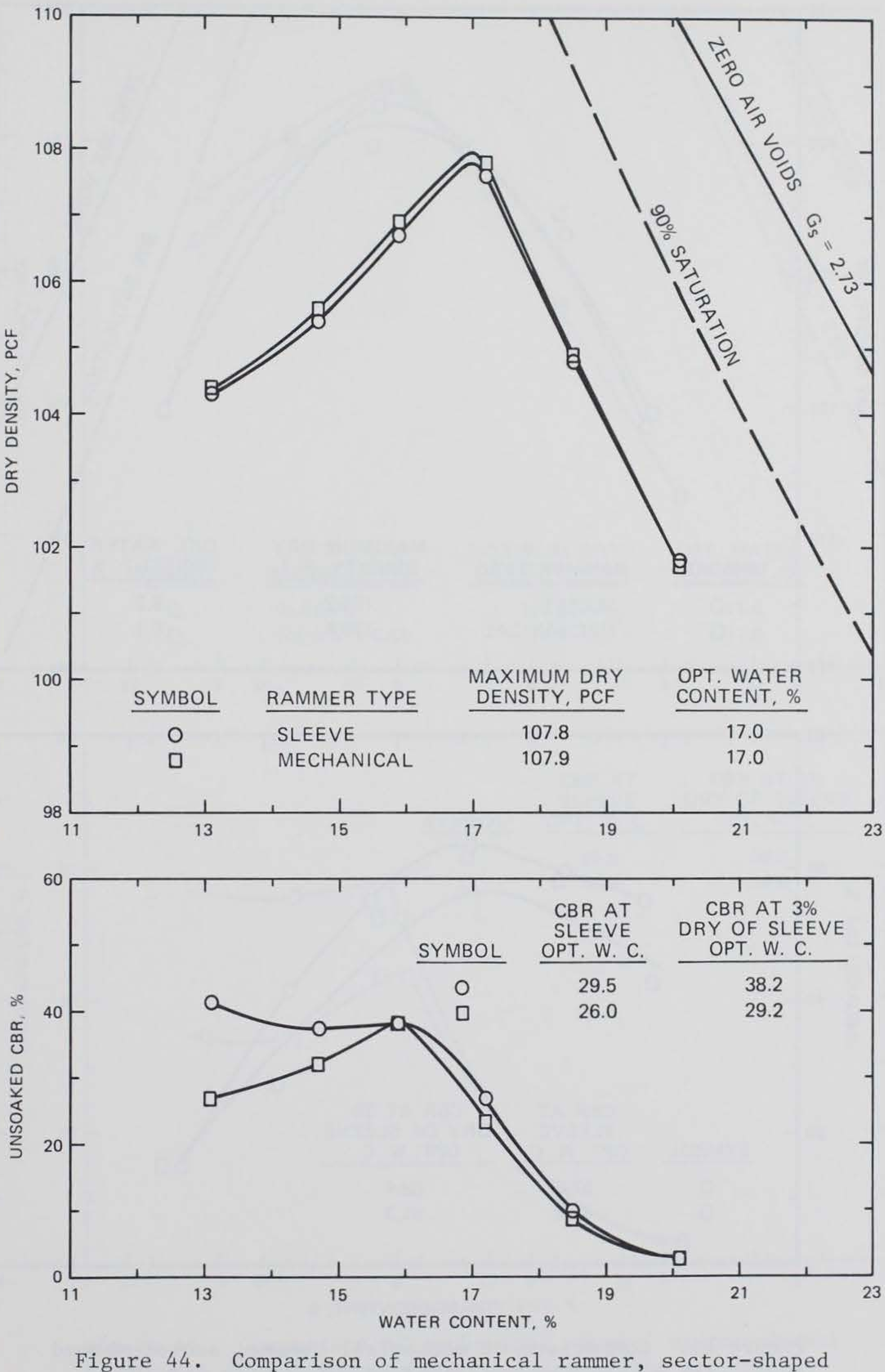
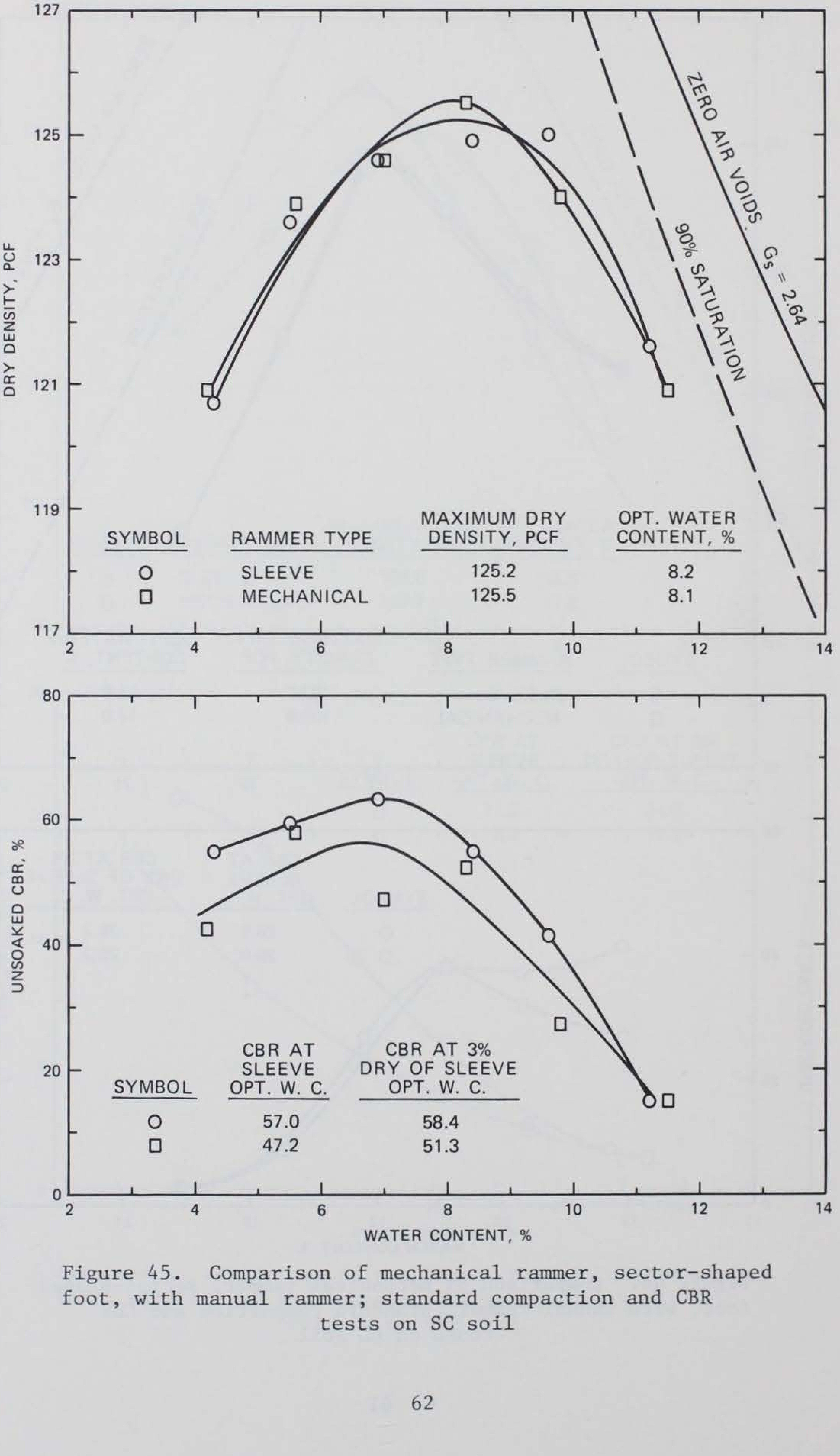


Figure 44. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; standard compaction and CBR tests on CL soil



SYMBOL	RAMMER TYPE	MAXIMUM DRY DENSITY, PCF	OPT. WATER CONTENT, %
○	SLEEVE	125.2	8.2
□	MECHANICAL	125.5	8.1

SYMBOL	CBR AT SLEEVE OPT. W. C.	CBR AT 3% DRY OF SLEEVE OPT. W. C.
○	57.0	58.4
□	47.2	51.3

Figure 45. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; standard compaction and CBR tests on SC soil

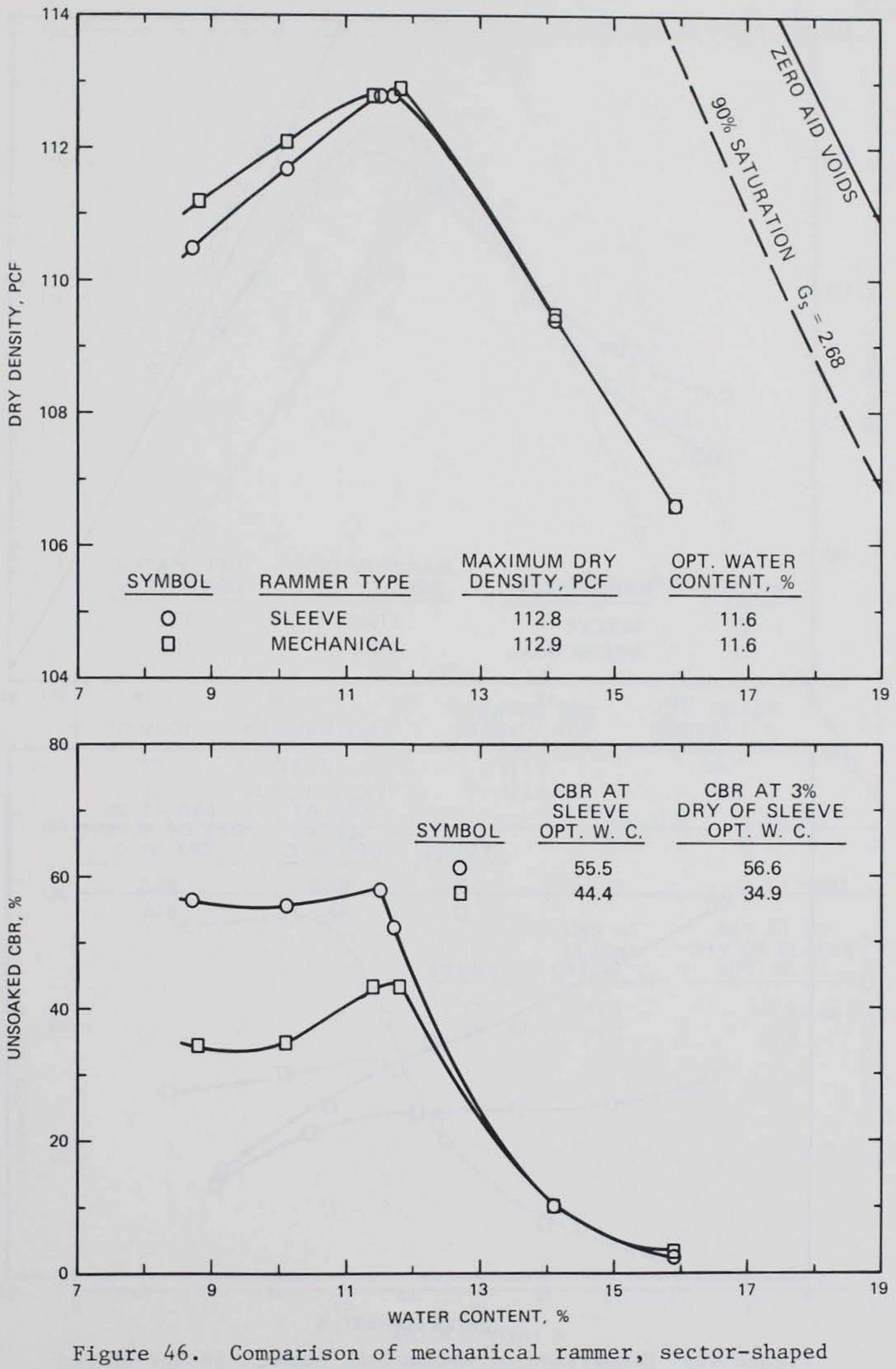


Figure 46. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; standard compaction and CBR tests on SM soil

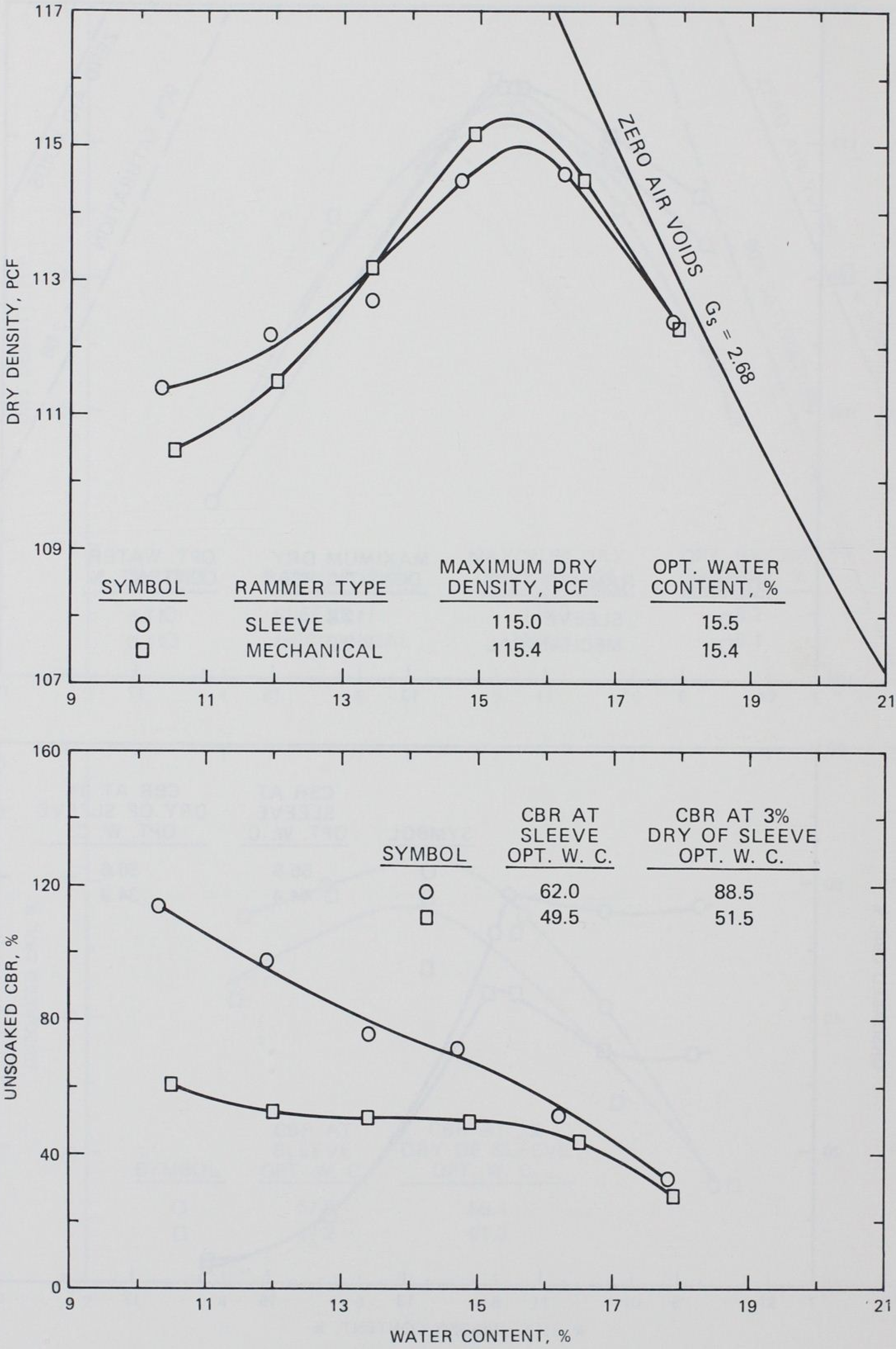


Figure 47. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; modified compaction and CBR tests on CH soil

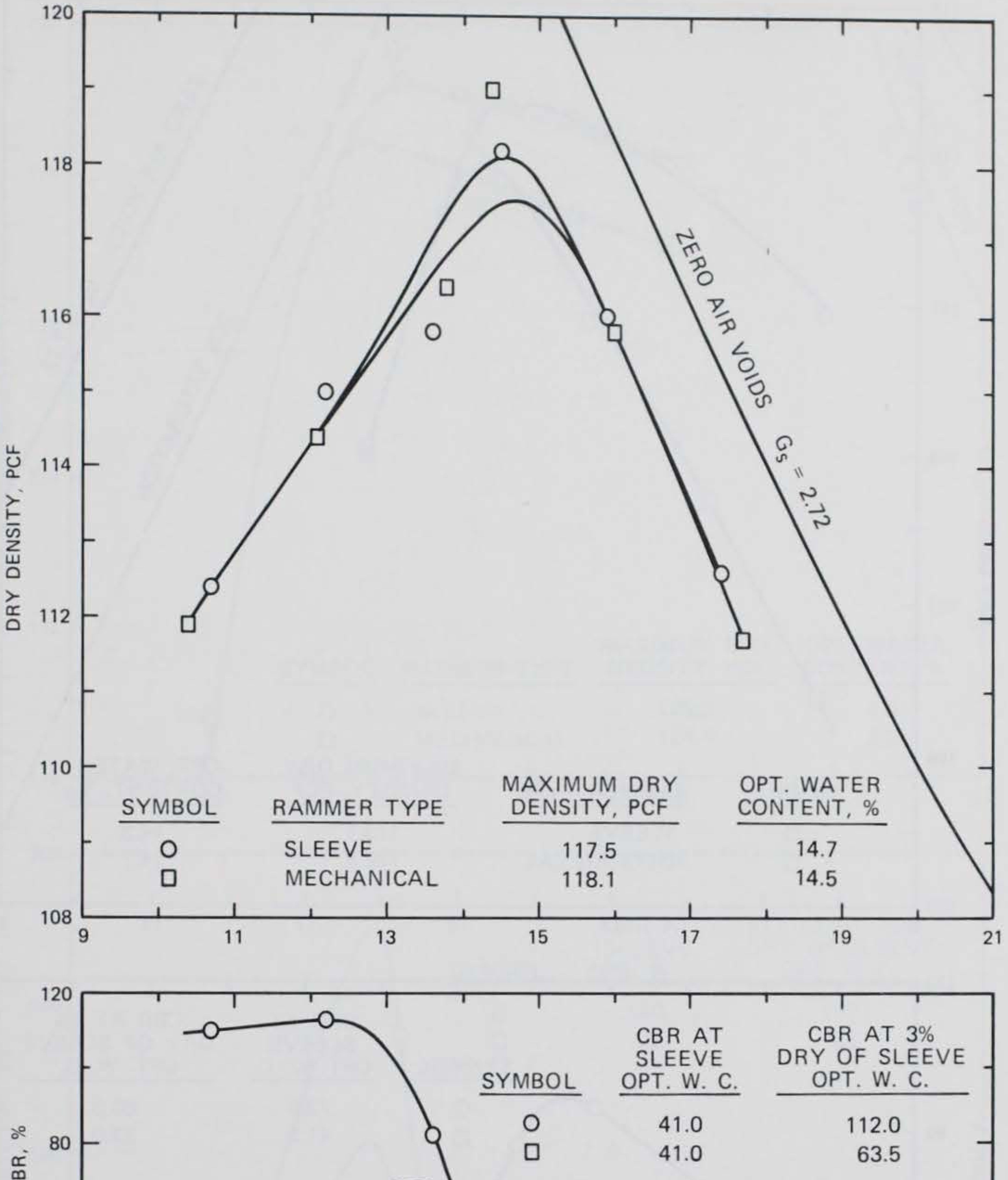


Figure 48. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; modified compaction and CBR tests on CL2 soil

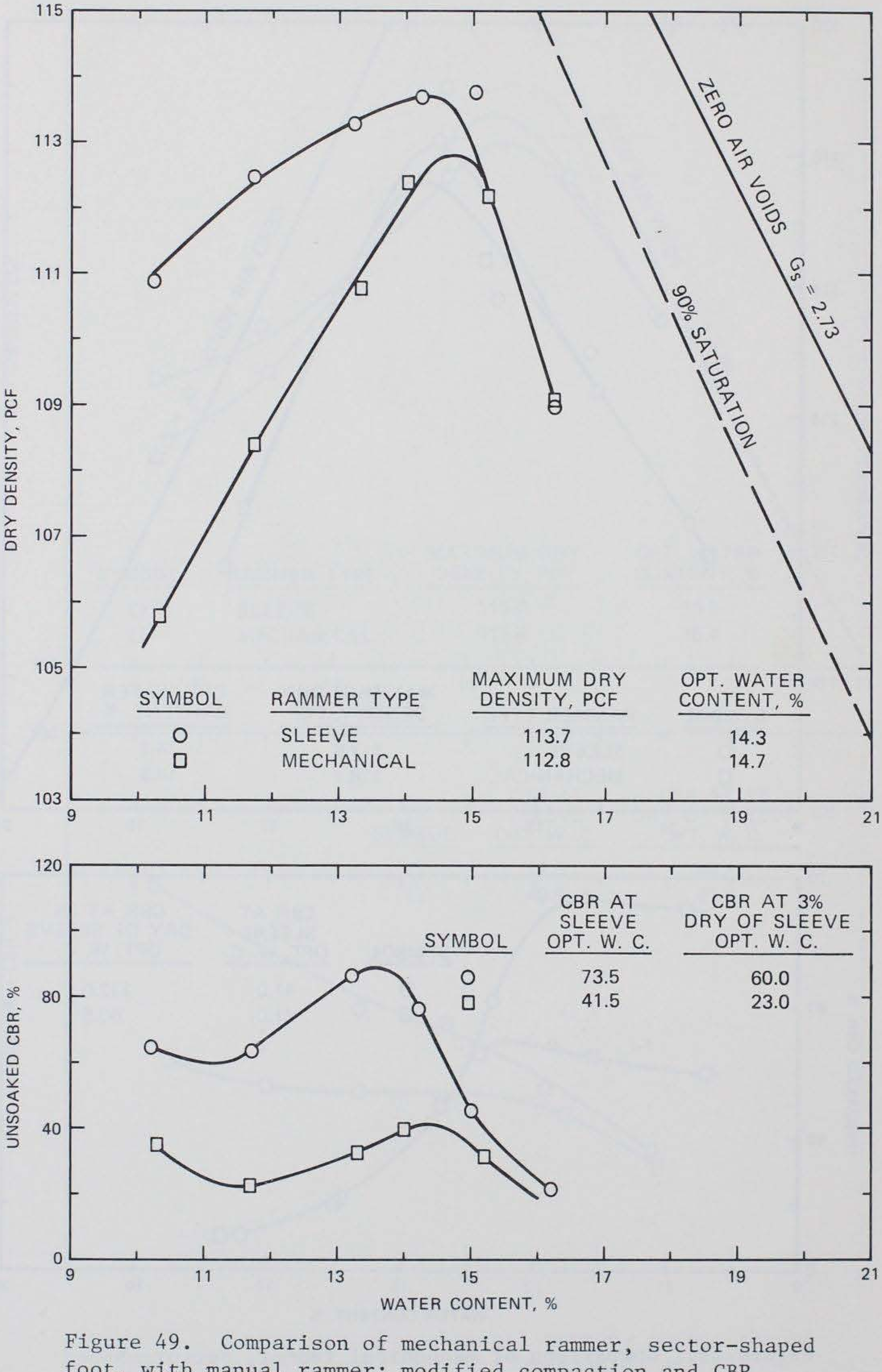


Figure 49. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; modified compaction and CBR tests on CL soil

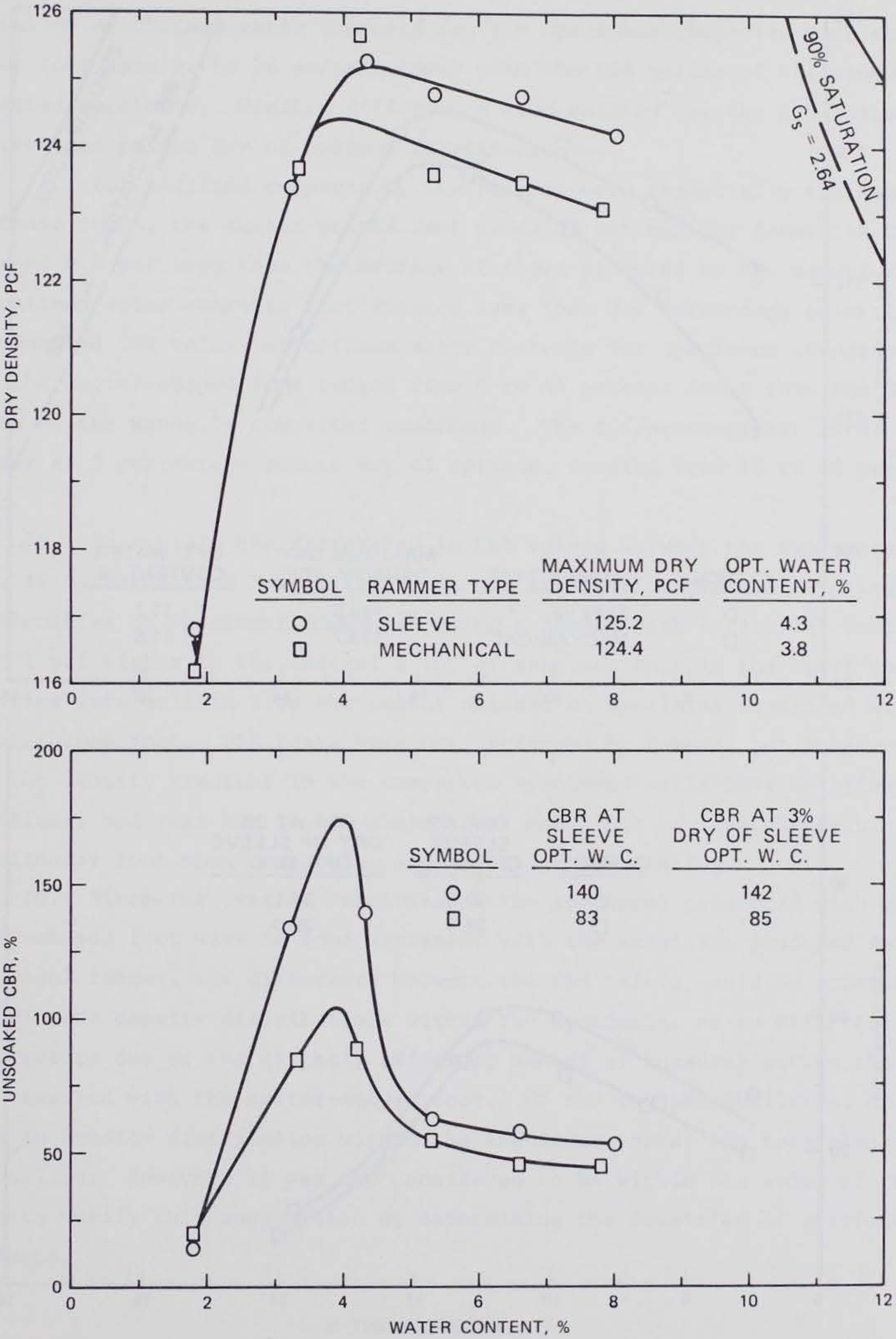


Figure 50. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; modified compaction and CBR tests on SC soil

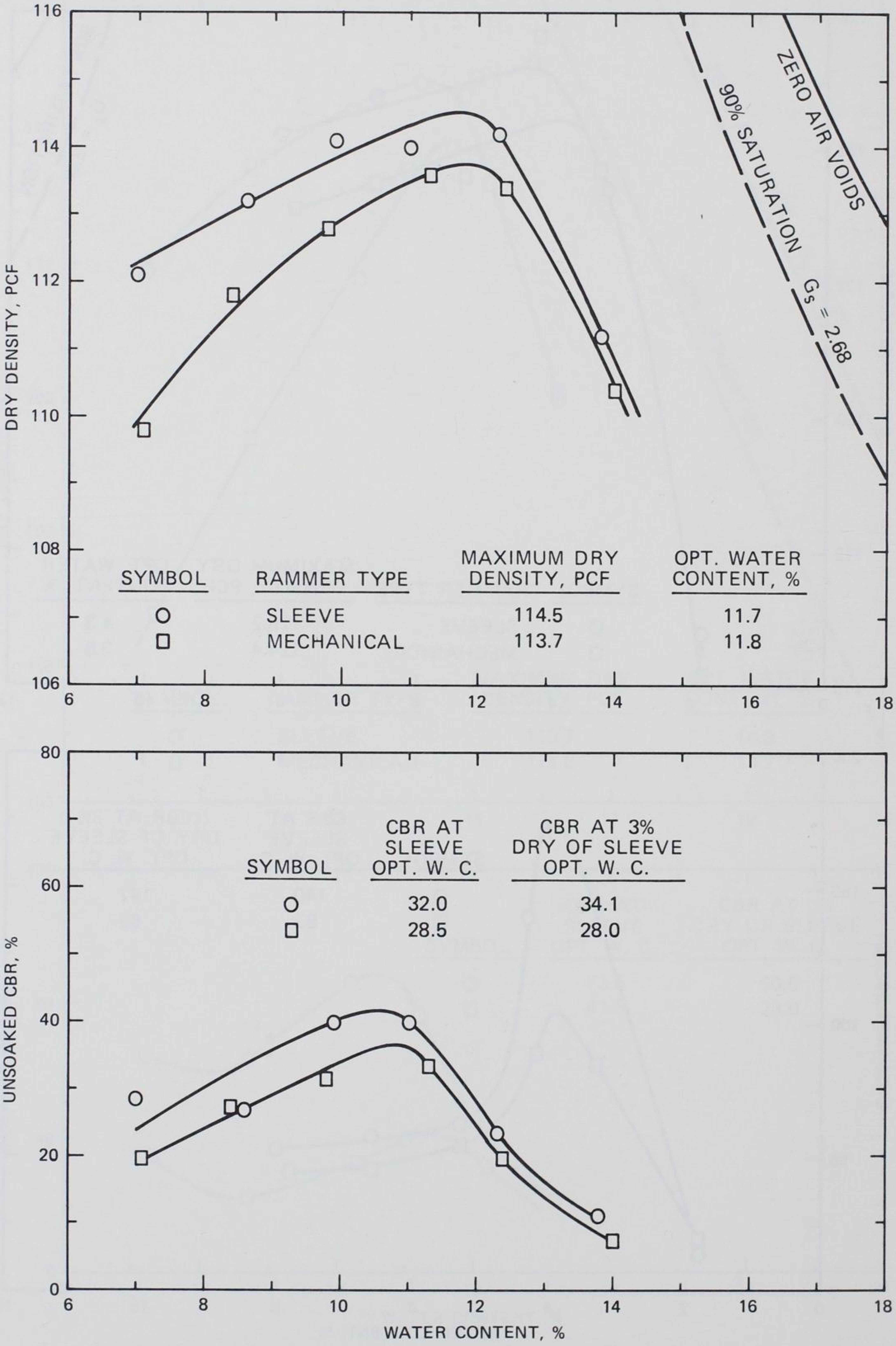


Figure 51. Comparison of mechanical rammer, sector-shaped foot, with manual rammer; modified compaction and CBR tests on SM soil

CBR values at optimum water contents for the specimens compacted with the sector foot were 12 to 38 percent lower than the CBR values of the manually compacted specimens. Similar differences also existed for the CBR values at 3 percentage points dry of optimum water contents.

74. For modified compaction, the results were essentially the same. For these tests, the sector-shaped foot produced maximum dry densities that averaged 0.3 pcf less than the average of those produced by the manual rammer and optimum water contents that averged less than 0.1 percentage point less. The unsoaked CBR values at optimum water contents for specimens compacted with the sector-shaped foot ranged from 0 to 44 percent lower than the CBR values of the manually compacted specimens. The differences were even greater at 3 percentage points dry of optimum, ranging from 18 to 62 percent lower.

75. To explain the difference in CBR values between the two types of feet, it is noted that Dawson (1959) in his study of compaction reported that the densities of specimens compacted using a rammer with a circular foot were about 1 pcf higher in the central 2 in. of specimen than in the outer portion. Densities were uniform from the center outward on specimens compacted with a sector-shaped foot. CBR tests were not performed by Dawson, but he speculated that the density gradient in the compacted specimens would have an effect on CBR values, and that the sector-shaped foot would not be interchangeable with the circular foot when compacting specimens for CBR testing.

76. Since the overall densities of the specimens compacted with the sector-shaped foot were in good agreement with the densities produced using the manual rammer, the difference between the CBR values could be attributed to different density distributions within the specimens, or to differences in structure due to the slightly different amount of kneading action that may have occurred with the sector-shaped foot. Of the two possibilities, differences in density distribution within the specimens appear the more plausible explanation. However, it was not considered to be within the scope of this study to verify this supposition by determining the densities of sections of specimens.

Evaluation of Procedures for Calibrating Mechanical Rammers

77. Two methods are currently used to calibrate mechanical compactors. One is to compare the results of compaction on soil using a manual rammer with results using a mechanical rammer and the other is to compare the deformations of lead test cylinders by both a mechanical and a hand rammer. The primary advantage in using soil for calibration is that it includes all the variables that might affect the results of compaction, and no interpretation of the results is needed; that is, it is not necessary to correlate differences in calibration results with differences in soil density. The main disadvantages of using soil are that:

a. A soil having the desired property of high plasticity is not always available when the calibration is needed.

b. The calibration requires careful preparation of the soil, a wait for curing of soil before compaction, and wait for water content results after compaction.

78. Desirable aspects of a method involving compaction of air-dry soil or some other compactible material are that:

a. It matches the compaction operation as it actually is performed (thus accounting for potential sources of error such as the mechanical rammer not dropping a full 12 in. with respect to the uncompacted soil surface), while eliminating the need for lengthy specimen preparation and water content determination.

b. It makes available a material with known compaction characteristics that could act as a standard and not required repeated reference to compaction with a hand-held rammer.

79. Desirable attributes of a device that provides an index of work done during rammer impacts are that:

a. It would be convenient to use. For example, test values could be read directly from a scale without the need for accessory equipment such as dial gages or calipers.

b. It could act as a reference and not require repeated comparison to the results of hand rammers.

80. With the above-mentioned considerations in mind, the following methods of calibrating mechanical rammers were suggested:

a. Compaction test on air-dry soil.

b. Compaction test on dry granular material (horticultural perlite).

c. Compaction test on artificial soil (soil-oil mixture similar to modeling clay).

d. Rammer impacts on coil spring.

e. Rammer impacts on rubber cylinder (spring).

f. Rammer impacts on friction brake (damper).

g. Rammer impacts on load cell and display.

h. Rammer impacts on lead cylinders using ASTM apparatus.

i. Rammer impacts on lead cylinders omitting ASTM apparatus.

j. Measurement of rammer impact velocity using photocell combined with weighing of drop weight.

Of the methods listed, methods g and j could only be considered of use for a central laboratory with appropriate facilities. However, for calibration of large-scale compaction equipment, these devices were considered of potential use and therefore given consideration. Of the methods listed, the artificial soil idea, c, was rejected as having no practical advantage over conventional soil since it would have to be reprocessed after each use. The perlite, coil spring, friction brake, and measurement of impact velocity using a photocell were given preliminary evaluation and were rejected because they were either insensitive to differences in impact energy (the coil spring), did not provide consistent and reproducible results (the friction brake), had practical drawbacks such as messiness (perlite), were difficult to set up (photocell), or were difficult to use (coil spring causing rammers to rebound excessively).

81. For each of the methods given further evaluation, a series of trials were performed using (a) the 5.5-lb sleeve rammer, (b) the mechanical rammer set to a 12-in. height of drop, and (c) the mechanical rammer set to the height of drop required to match the results of the 5.5-lb sleeve rammer in standard compaction tests on CH soil.

Compaction on moist soil

82. Compaction curves for the mechanical compactor in the original and adjusted condition and companion curves obtained with the manual rammer are shown in Figures 52 and 53. Included in both figures are the data for the air-dry specimens of CH soil presented and discussed in the section on compaction on air-dry soil. These specimens can be seen to have water contents in the air-dry condition of 5.8-6.6 percent.

83. The results are summarized below:

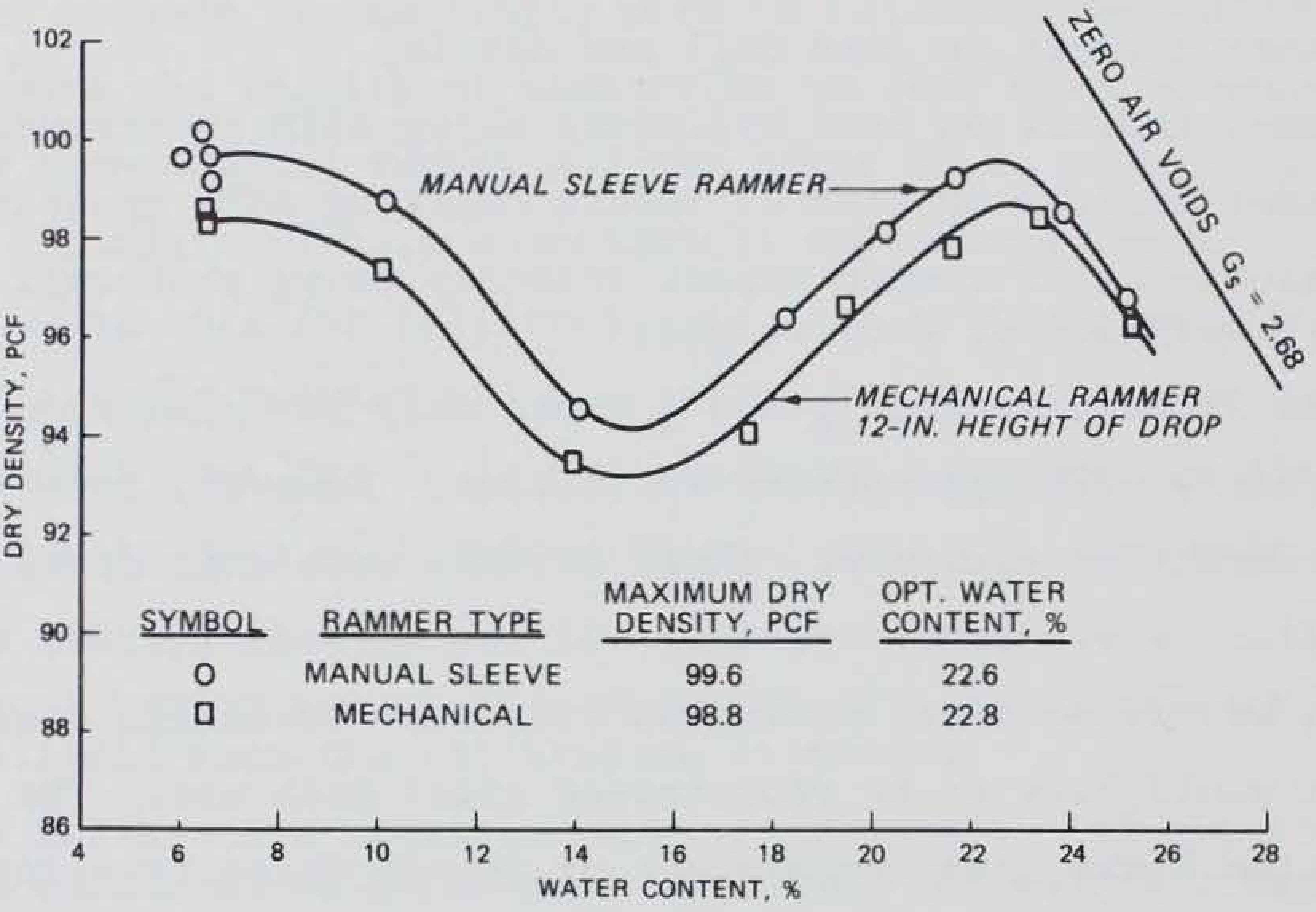


Figure 52. Comparison of mechanical rammer at 12-in. drop with manual rammer using standard compaction on CH soil

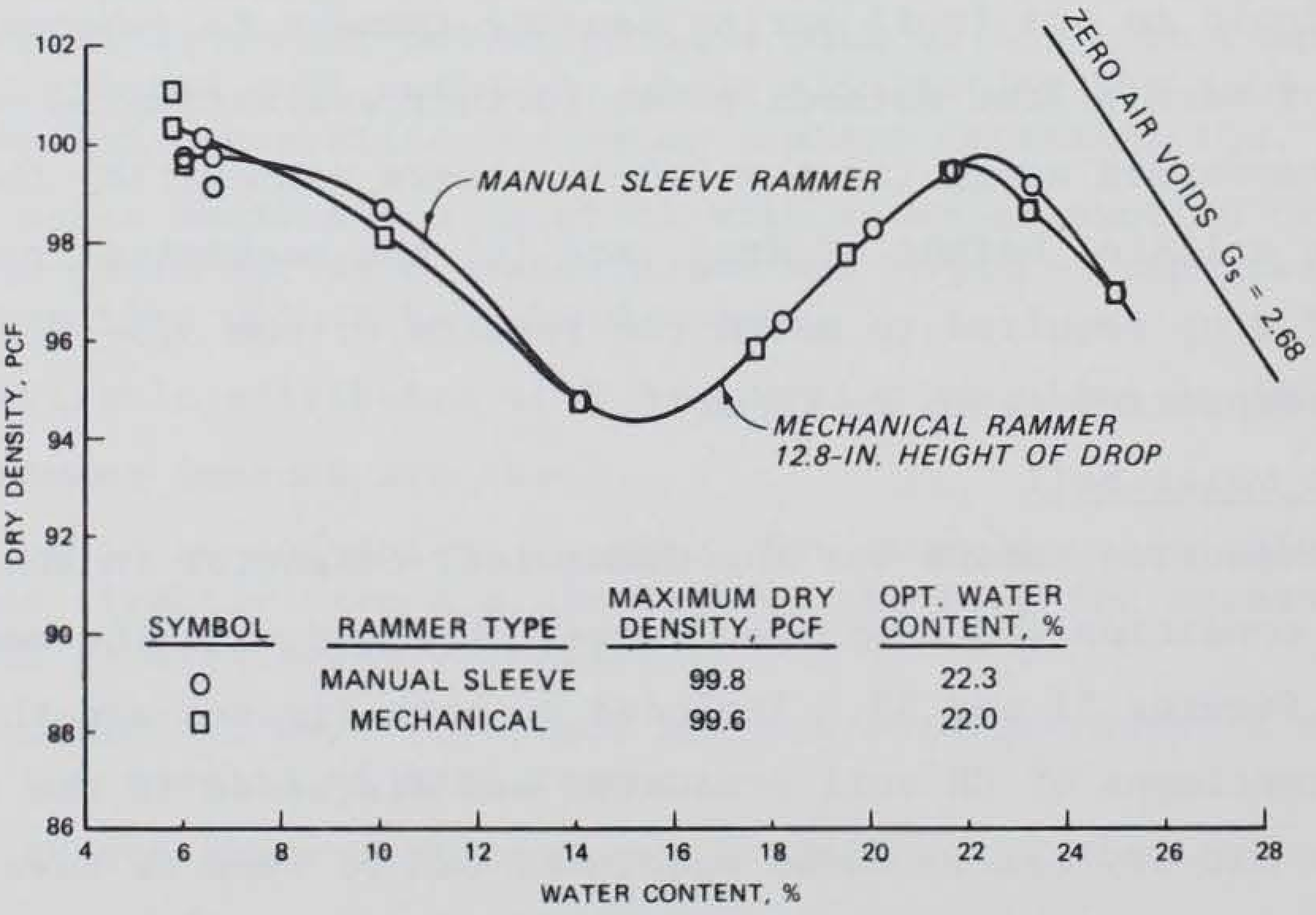


Figure 53. Comparison of mechanical rammer at 2.8-in. drop with manual rammer using standard compaction on CH soil

Rammer	$\gamma_{d\ max}$ pcf	w opt percent	Dry Density as Percentage of Average Manual Value
Sleeve	99.6	22.6	99.9
Mechanical (12-in. drop)	98.8	22.8	99.1
Sleeve	99.8	22.3	100.1
Mechanical (12.8-in. drop)	99.6	22.0	99.9

The results show that after adjustment, the compaction curves were virtually identical not only at optimum water content, but throughout the range of water contents tested. However, the curves in Figure 52 indicate that the difference in density resulting from a difference in compactive effort becomes slightly greater as water content decreases from optimum to the air-dry condition. Thus, comparing the dry densities of soil specimens at any water content dry of optimum may indicate differences in compactive effort at least as well as specimens compacted near optimum.

Compaction on air-dry soil

84. Results for compaction on air-dry soils are shown in Table 7. The data for air-dry CH soil are also plotted in Figures 52 and 53. The data for air-dry specimens of CH soil indicate that calibration using air-dry soil would be at least as good as calibration using soil near optimum water content for determination of differences between manual and machine compaction effort. However, tests on the air-dry CL2 soil did not show any difference between the mechanical rammer at the 12- and 12.8-in. heights of drop. Tests were not performed comparing the rammers using CL2 soil at water contents near optimum, so it cannot be concluded whether a greater difference would have shown up at these water contents. Several specimens of the air-dry CL soil were also compacted. However, when compacting these specimens, the soil tended to fluff excessively and be blown out of the mold by air currents from the falling rammer. Thus, the use of air-dry soil in calibration tests may not be practical for all types of soil.

Lead cylinder deformation in ASTM apparatus

85. Results of tests using lead cylinders in the ASTM apparatus are shown in Table 8. Included in the table are results of trials using the new 5.5-lb sliding-weight rammer and slotted-sleeve rammer.

Lead cylinder deformation in simplified apparatus

86. Results of tests using lead cylinders in the simplified apparatus are shown in Table 9. Included in the table are results for trials using the 10-lb sleeve rammer, the new 5.5-lb sliding-weight rammer, and the new 10-lb sliding-weight rammer.

Rubber deflection calibration device

87. The results of tests using this device are summarized in Table 12. It can be noted from the table that while the relative magnitude of deflections recorded for the various calibrations is consistent with the results of the tests on soil, the difference in deflections between the rammers is relatively small, being a maximum of 0.015-in. for the difference between a mechanical rammer at 12 and 12.8 in. Thus the rubber calibration device did not satisfy one of the desirable attributes stated in paragraph 79; that is, it was not a device that recorded deflections great enough to be conveniently read from a graduated scale. A deflection of 0.02 in. was considered the minimum deflection easily read directly from a scale.

Load cell

88. Results of tests using this device are shown in Table 11. Included in the table are results for trials using the 10-lb sleeve rammer and the 5.5-lb slotted sleeve rammer, the new 5.5-lb sliding-weight rammer, and the new 10-lb sliding-weight rammer.

Comparison of calibration devices

89. A comparison of the results of the four calibration devices is shown in Table 12. None of the calibration devices was entirely satisfactory. All except the rubber cylinder device had discrepancies in the values produced with respect to the results on soil. However, the rubber cylinder device varied considerably in results it produced in different calibrations with the manual rammers.

90. The load cell calibrations on the other hand indicated a great discrepancy between results using the manual sleeve rammers and those using the mechanical rammer. When the height of drop was adjusted to match the manual rammer on soil, the mechanical rammer indicated only 75.6 percent of the peak load indicated for the manual sleeve rammer. The sliding-weight rammer produced peak values 95.2 percent of those recorded for the sleeve rammer.

91. In comparing the deformations of lead cylinders in the simplified apparatus, the mechanical rammer produced deformations 4 percent greater than the sleeve rammer when the mechanical rammer was adjusted to duplicate the sleeve rammer results on soil. Deformations produced by the sliding-weight rammer are about 4 percent less than those produced by the sleeve rammer. Thus a discrepancy exists between results obtained using the lead cylinders and results using soil. However, the data summary (Figure 11) also shows that the deformations of lead cylinders in the simplified apparatus give results having the smallest variance from sample to sample and trial to trial within samples. It was also the only device that gave uniform results for the new sliding-weight rammer.

92. Comparing the deformations of lead cylinders in the ASTM apparatus shows that the mechanical rammer adjusted to match the sleeve rammer on soil produced deformations about 2 percent less than produced by the sleeve rammer. The unadjusted mechanical rammer and the sliding-weight rammer produced values 14 and 22 percent less than the sleeve rammer, respectively.

Discussion and analysis of calibrations using repeated trials

93. After collection of the calibration data using the various devices, a statistical analysis of the data was made to develop an effective approach to deciding when a mechanical rammer was in satisfactory adjustment. The data from the lead cylinders deformed in the ASTM apparatus were taken for analysis.

94. The ASTM standard D 2168-80, "Calibration of Laboratory Mechanical Rammer Soil Compactors," permits calibration of mechanical rammers either by comparison of maximum dry densities obtained from the compaction soil using both a manual rammer and a mechanical rammer, or by comparison of lead cylinder deformations. For calibration with lead cylinders, the standard states that deformation trials are to be made with a manual rammer "until five deformation values are obtained that do not vary more than 2.0 percent from the average value; that is the absolute value of υ_1 [the percent deviation of any one trial from the average] must be less than 2.0 for the five values selected" for averaging (American Society for Testing and Materials 1981). The operation of deforming a series of lead cylinders is then repeated for the mechanical rammer, and if the mechanical rammer average deformation value produced by the mechanical rammer is greater than 2.0 percent different

from the manual rammer value, two more series of trials are performed to get two more sets of data. These three sets of trials from the mechanical rammer are then averaged and compared to the average of the set of trials from the manual rammer. If after collection and averaging of the three sets of trials, the average mechanical rammer value differs from the average manual rammer value by greater than 2.0 percent, the drop weight of mechanical rammer must be adjusted and the calibration repeated.

95. The ASTM procedure just described has several flaws: (a) it discards data that there is no statistical justification for discarding; (b) it is possible that the addition of one more deformation value to a set of values can lead to more than one group of five values within that set which satisfies the ±2 percent criterion, while having different means (when this happens, there is no rational basis for choosing one group of values over the other, hence different persons could choose different means from the same data); and (c) when the means of the manual and mechanical rammer disagree, the ASTM procedure implicitly assumes a greater potential for error in the mechanical rammer and calls for two more sets of mechanical rammer data. However there appears to be no rational basis for this assumption; it is equally likely (and possibly more likely) that the manual rammer has the greater variability. Consequently, for this study all the values recorded for a set of trials were used in calculations for that set of trials. If there was some obvious reason for discarding a trial, such as a misstruck blow, the value was not recorded.

96. Any calibration procedure must establish, with a suitable degree of confidence, whether the mean of the impacts for the mechanical rammer is equal to the mean for the manual rammer. The procedure must also establish the number of trials required to determine this difference with a given degree of confidence. To provide as much information for analysis as possible, data reported by Durham and Hale for lead cylinder trials on both manual and mechanical rammers was summarized along with comparable data from this study, and is presented in Table 13 (Durham and Hale 1977). Frequency histograms were prepared for the data, and it was concluded that the frequency distributions for all the rammers approximated the standard normal distribution.

97. Given that the data are at least approximately normally distributed, a sampling distribution approximated by the Student-t distribution can be used to test the significance of the difference between two means. The statistic

is given by the formula (Miller and Freund 1965, Duncan 1959):

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - \delta}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where

t = the Student-t distribution with υ degrees of freedom given by

$$\upsilon = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2 - 1}}$$

and

$\bar{x}_1$, $\bar{x}_2$ are sample means.

n_1 , n_2 are sample sizes.

δ is the difference between the true (infinite sample size) means of the populations from which $\bar{x}_1$ and $\bar{x}_2$ are taken.

s_1 , s_2 are sample standard deviations.

The above statistic was chosen since it is suitable for use with small samples and with samples from populations having standard deviations which are not necessarily equal. As can be seen in Table 13, the standard deviations of the samples for the various rammers varies considerably so it was not considered justified to assume that the population standard deviations were the same.

98. A criterion for deciding when adjustment of the mechanical rammer is necessary will be established as follows:

a. A weighted average of all the manual rammer deformation trials for this study (second part of Table 13) was calculated to be 174.2 mils. The deformation values for the mechanical rammer at 12.0-in. height of drop varied considerably. Since the average deformation for the mechanical rammer varied significantly with time the value 159.2 was used since it was obtained within 2 days of the time when the mechanical rammer was calibrated using soil. The difference of 15 mils between the manual rammer average deformation value and the selected mechanical rammer value was taken as equivalent to the approximately 1-pcf difference in maximum dry density between the mechanical and manual rammers measured in calibrations of the mechanical rammer using soil. This was considered to be the maximum difference in compaction results that should be permitted without requiring a readjustment of the mechanical rammer. Thus, δ is made equal to 15 mils.

b. It was desired to be 99 percent confident that the difference of 15 mils or greater between the true average deformation values of the manual and mechanical rammers results in a decision to readjust the mechanical rammer. That is, the difference δ between the true means of the two rammers must not exceed 15 mils with a probability greater than 0.01.

c. It is desired to be 90 percent confident that the mechanical rammer is not adjusted unnecessarily. That is, there must be no more than 0.1 probability that the true means for the two rammers are actually identical ($\delta = 0$) when a decision is made to readjust the mechanical rammer. Since the sample mean of the mechanical rammer can be either greater than or less than the mean of the manual rammer, the probability of its being one or the other must be no greater than 0.05.

99. Let C represent the maximum difference between the manual and mechanical rammer sample means that will be permitted before recalibration is required. To find the interval, C , that satisfies a, b, and c, above, the equation for t can be rearranged to

$$\text{Constant} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} = \frac{(\bar{X}_1 - \bar{X}_2) - \delta}{t}$$

To satisfy a and b

$$\text{Constant} = \frac{\delta - C}{t_{(0.01)}}$$

and to satisfy c

$$\text{Constant} = \frac{C}{t_{(0.05)}}$$

Equating the two conditions in terms of the constant sample size and sample standard deviation term,

$$\frac{\delta - C}{t_{(0.01)}} = \frac{C}{t_{(0.05)}}$$

or

$$C = \frac{\delta}{\frac{t_{(0.01)}}{t_{(0.05)}} + 1}$$

Since values for t depend on n_1 , n_2 , s_1 , and s_2 , the problem can be simplified by letting $n_1 = n_2 = n$ and $s_1 = s_2 = s$, and referring to statistical tables for the values of t for a given degree of freedom, υ . Table 14 shows the values of t and the resulting C for various sample sizes. The table indicates that the confidence limits for the difference between the two rammers is approximately 6. Thus, the mechanical rammer should be readjusted when $|\overline{X}_1 - \overline{X}_2| \geq 6$.

100. The simplified equation for t is:

$$t = \frac{(\overline{X}_1 - \overline{X}_2) - \delta}{s} \sqrt{\frac{n}{2}}$$

101. Using the requirement that there be 90 percent confidence that the mechanical rammer not be adjusted unnecessarily, the equation can be further simplified and rearranged to

$$s = \frac{C}{t_{(0.05)}} \sqrt{\frac{n}{2}}$$

Results of calculation of s using this formula are presented in Table 14.

102. It will be noted that the table includes additional columns headed d_2 , $d_2\sigma$, and R_{max} . Normally the best estimate of a population standard deviation, σ , is the standard deviation, s , of a sample from the population. However, for small samples a statistic based on the sample range, R , can be developed that is nearly as good as s for estimating the population standard deviation (Duncan 1959). The relationship between the range and population standard deviation is given by

$$\sigma = \frac{R}{d_2}$$

where d_2 is a constant that depends on sample size. The constants d_2 (obtained from Duncan (1959)) are given in the table for sample sizes up to 12. Beyond a sample size of 12, it is sufficiently more accurate to calculate s for each of the samples to warrant doing so. The column R gives the most probable range for the given sample size and standard deviation, assuming that $\sigma = s$. This column can be used to estimate the required sample size for a set of deformation trials by performing a small number, for example five, and comparing the range of the sample with the corresponding value of R for the size, n , of the sample. If the range of the sample exceeds R , then additional trials should be made until the range of the sample becomes less than R . If the sample standard deviation has been calculated, it can be used instead of R to judge sample size adequacy.

103. While this approach can be extended to any sample size, examination of the sample standard deviations found in Table 13 for both the manual and mechanical rammers leads to the conclusion that, if the sample standard deviations for the mechanical rammers are greater than about 6 or the sample standard deviations for the manual rammer are greater than about 10, either the rammer or calibration apparatus is in need of repair or the technique for applying blows should be improved.

104. The approach just developed for judging the adequacy of the ASTM lead cylinder trials can be generalized to all the calibration devices by expressing the data in terms of percentages of the average manual sleeve rammer value. The last column in Table 14 gives maximum permissible ranges expressed as percentages of the average manual rammer deformation value, and in Table 12, the maximum range criterion is applied to all the calibration devices.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

105. The following conclusions were based on data collected, observations made in this testing program, and reports of testing by others and reported herein:

a. The 10-lb sliding-weight type rammer specified in Military Standard MIL-STD-621A produces lower maximum dry densities and higher optimum water contents than an ASTM specification sleeve-type rammer when both rammers are tested at a slow rate-of-blow application with carefully applied blows (Figures 19-28 and Table 4).

b. The 10-lb sliding-weight type rammer with solid foot specified in Engineer Manual EM 1110-2-1906 produces lower maximum dry densities and higher optimum water contents than an ASTM specification sleeve-type rammer when both rammers are tested at a slow rate-of-blow application with carefully applied blows (Figures 19-28 and Table 4). Experience at WES and reports from other CE laboratories also indicate that 10-lb rammers of the solid foot design are subject to rapid failure due to the breaking of the foot from the guide rod.

c. A new 10-lb sliding-weight rammer with movable spring-loaded foot developed during this study produces slightly lower maximum dry densities (less than 1 pcf) and slightly higher optimum water contents (less than 1 percentage point) than an ASTM specification sleeve-type rammer when both rammers are tested at a slow rate-of-blow application with carefully applied blows (Figures 29-38 and Table 5). The sliding-weight rammer required somewhat less effort to use than the sleeve-type rammer.

d. A new 5.5-lb sliding-weight rammer with moveable spring-loaded foot developed during this study produces slightly lower maximum dry densities (less than 1 pcf) and about the same optimum water contents as an ASTM specification sleeve-type rammer when both rammers are used at a slow rate-of-blow application with carefully applied blows. The two rammers were about equally easy to use (Figures 11-18 and Table 3).

e. Previous investigations have shown that an increase in dry density is produced by both sleeve- and sliding-weight type rammers with increasing rate-of-blow application. However, the magnitude of this increase varies from operator to operator and depends on the type of rammer. The effect of rate-of-blow application will be minimized if the rate is kept below 40 blows/min.

f. Complete air-drying and rewetting of a soil prior to compaction gives results different from those given when the soil has been only partially air-dried or has not had to be dried at all; i.e., the soil is dried only to the water content desired for the driest point on the compaction curve or the natural water content of the soil is either at or below that desired for the driest point on the curve. Differences in compaction results also occur when a soil which has not been air-dried is or is not permitted to cure after adding water prior to compaction; the differences are less, however, than those given by complete air-drying versus partial or no air-drying.

g. The use of the sector-shaped foot on a mechanical rammer when compacting soil in a 6-in.-diam mold produces the same maximum dry densities at optimum water contents as are obtained with a manual rammer for either standard or modified compaction. The mechanical rammer equipped with sector-shaped foot produces compacted specimens with substantially lower CBR values than specimens compacted with a manual rammer.

h. The calibration of mechanical compactors can be performed by comparing the compaction curve produced by a manual rammer with the compaction curve produced by a mechanical rammer and adjusting the height of drop or drop weight of the mechanical rammer to produce the same maximum dry density and optimum water content. Calibration of mechanical compactors can also be performed by using the lead test cylinders and apparatus described in ASTM Method D 2168-80. However, the number of trials required to obtain acceptably accurate results must be based on the variability of the rammers used in the calibration rather than by the selection technique currently specified.

i. A calibration apparatus incorporating a rubber cylinder as described in this study may be used to calibrate a mechanical rammer by comparing deflections under the impact of a mechanical rammer with deflections under the impact of a manual rammer. However, the device offers no improvement over the ASTM lead test cylinder calibration.

Recommendations

106. In view of (a) the inability of the sliding-weight rammers currently specified in EM 1110-2-1906 to provide appropriate consistent compactive effort, (b) the effect of rate-of-blow application on results using sliding-weight type rammers, and (c) the higher cost of fabricating sliding-weight type rammers, it is recommended that the sleeve-type rammer be specified for compaction testing on CE civil works projects. Additionally, there is increasing Government emphasis on the adoption and voluntary use of test standards developed by national standards organizations for construction quality control and quality assurance testing on CE projects where such standards satisfy Government requirements. Finally, the adoption of sleeve rammers for CE civil works testing will reduce the chances for error and conflict when CE test methods are specified, together with other test methods such as those

by ASTM or AASHTO, for design and construction testing on a single project.

107. It is also recommended that the feasibility of adopting the sleeve-type rammer for MIL STD 621-A be determined. Army TM 5-530, "Materials Testing," specifies a sleeve-type 10-lb rammer, while MIL STD 621-A specifies a 10-lb sliding-weight type. The standardization of the military and civil rammers would result in lower equipment costs and eliminate confusion and error which could occur because of the variety of rammers now required in the laboratory to satisfy various specifications--Civil, Military, ASTM, and AASHTO.

108. In addition to the foregoing, it is recommended that Appendices VI, "Compaction Tests," and VIA, "Compaction Tests for Earth-Rock Mixtures," of EM 1110-2-1906 be revised to include limits on the rate-of-blow application for manual rammers, a cautionary note explaining the possible differences in results that may occur with different methods of preparing the soil for compaction, and procedures for the calibration of mechanical rammers including the use of soil and the use of lead test cylinders.

109. It is recommended that the sector-shaped foot be permitted for use with mechanical compactors when compacting soil in a 6-in.-diam mold unless the compacted specimens are used for CBR testing. Specimens compacted for CBR tests should be compacted with a rammer having a circular foot only.

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Table 1

Mold Weights and Dimensions

Compaction Molds

Nominal Mold Size in.	Inside Diameter in.	Height in.	Volume cu ft	Weight Without Base g
4	3.995	4.584	0.03325	2106
6	5.993	4.585	0.07485	3068

CBR Molds

Mold Identification Number	Inside Diameter, in.	Specimen Height* in.	Specimen Volume cu ft	Mass Including Base g
3	6.002	4.585	0.07507	10634
16	6.003	4.579	0.07500	11038
26	6.003	4.591	0.07520	10597
41	6.004	4.571	0.07489	10335
49	6.004	4.590	0.07520	10882
57	6.004	4.581	0.07506	10901

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* Using 3.416-in.-thick spacer. Nominal total height of CBR molds is 8 in.

Table 2

Manual Rammer Weights and Dimensions

Type	Foot Diameter in.	Drop Height in.	Total Weight lb	Drop Weight lb	Foot Weight lb
ASTM D 698 sleeve	2.001	12-1/32	9.392	5.498	NA
New standard effort sliding weight	2.002	12	8.395	5.500	0.450
Slotted sleeve	2.000	12	8.591	5.489	NA
Standard effort solid foot sliding weight	1.997	11-31/32	9.894	5.509	4.385
Military MIL-STD 621A sliding weight	2.002	18-1/32	15.359	10.011	1.30
ASTM D 1557 sleeve	2.000	18	15.851	10.004	NA
Modified effort solid foot sliding weight	1.992	18	14.663	10.011	4.652
New modified effort sliding weight	2.001	18	14.398	10.004	0.747

Table 3

Summary of Compaction Test Results, 5.5-lb Rammers

Soil Type	Rammer Type	Max Dry Density pcf	Opt Water Content percent	Differences Other Rammer Minus Sleeve	
				Max γ_d pcf	Opt w percent
		Standard Compaction			
CH	Sleeve	98.7	23.2		
	NSW*	98.2	23.2	-0.5	0.0
	Slotted sleeve	99.0	23.1	0.3	-0.1
CL2	Sleeve	106.2	18.9		
	NSW	105.5	18.8	-0.7	-0.1
CL	Sleeve	107.1	17.5		
	NSW	107.0	17.7	-0.1	0.2
SC	Sleeve	126.4	8.7		
	NSW	125.6	8.6	-0.8	-0.1
	Slotted sleeve	125.3	8.5	-1.1	-0.2
SM	Sleeve	111.9	13.9		
	NSW	111.8	13.5	-0.1	-0.4
	Slotted sleeve	111.8	13.5	-0.1	-0.4
		15-Blow Compaction			
CH	Sleeve	93.4	25.8		
	NSW	03.0	25.8	-0.4	0.0
CL2	Sleeve	103.5	20.8		
	NSW	102.8	21.0	-0.7	0.2
CL	Sleeve	105.3	19.0		
	NSW	105.3	19.0	0.0	0.0

* New sliding weight rammer.

Table 4

Summary of Compaction Test Results, 10-lb Military and Solid-Foot Rammers

Soil Type	Technician	Rammer Type	Max Dry Density pcf	Opt Water Content percent	Differences Other Rammers Minus Sleeve: Max γ_d pcf	Differences Other Rammers Minus Sleeve: Opt w percent
		Modified Compaction				
CH	A	Sleeve	115.9	13.9		
		Military	114.6	14.5	-1.3	0.6
		Solid Foot	113.1	15.6	-2.8	1.7
CL2	A	Sleeve	117.0	14.2		
		Military	116.2	14.7	-0.8	0.5
		Solid Foot	115.7	14.8	-1.3	0.6
CL	A	Sleeve	114.4	14.7		
		Military	113.7	14.5	-0.6	-0.1
		Solid Foot	113.3	14.6	-1.0	0.0
SC	A	Sleeve	127.6	4.7		
		Military	126.9	4.9	-0.7	0.2
		Solid Foot	127.9	5.5	+0.3	0.8
SM	B	Sleeve	115.6	12.1		
		Military	115.1	12.0	-0.5	-0.1
		Solid Foot	115.1	12.1	-0.5	0.0
		CE-12 Compaction				
CH	A	Sleeve	101.2	12.3		
		Military	98.2	21.7	-3.0	0.4
		Solid Foot	98.7	21.7	-2.5	0.4
CL2	A	Sleeve	107.1	19.1		
		Military	105.4	19.2	-1.7	0.1
		Solid Foot	105.4	19.6	-1.7	0.5
CL	B	Sleeve	105.5	17.8		
		Military	105.5	17.8	0.0	0.0
		Solid Foot	105.6	17.6	0.1	-0.2
SC	A	Sleeve	122.9	9.0		
		Military	122.6	9.0	-0.3	0.0
		Solid Foot	122.9	9.0	0.0	0.0
SM	B	Sleeve	108.2	14.5		
		Military	107.5	14.5	-0.7	0.0
		Solid Foot	107.9	14.2	-0.3	-0.3

Table 5

Summary of Compaction Test Results, New 10-lb Sliding-Weight Rammer

					$\gamma_{d\,max}$ and w_{opt} Comparison: NSW - SL	
Soil Type	Technician	Rammer Type	d max pcf	w_{opt} percent	γ_d pcf	w percent
Modified Compaction						
CH	B	SL	115.7	14.6		
		NSW	115.6	14.9	-0.1	0.3
CL2	B	SL	116.9	14.5		
		NSW	116.9	14.5	0.0	0.0
CL	B	SL	114.4	14.7		
		NSW	114.0	14.8	-0.4	0.1
SC	B	SL	127.7	4.4		
		NSW	127.8	4.2	0.1	-0.2
SM	B	SL*	115.6	12.1		
		NSW	115.5	11.9	-0.1	-0.2
CE-12 Compaction						
CH	B	SL	100.0	21.5		
		NSW	99.6	22.3	-0.4	0.8
CL2	B	SL	106.6	19.0		
		NSW	106.0	19.3	-0.6	0.3
CL	B	SL*	105.5	17.8		
		NSW	105.7	17.7	0.2	-0.1
SC	B	SL	121.7	10.1		
		NSW	121.9	10.1	0.2	-0.1
SM	B	SL*	108.2	14.5		
		NSW	107.6	14.7	-0.6	0.2

* Same data as reported in Table 4.

Table 6

Comparison of Foot Shape on Compaction and CBR Tests

Sector/Auto versus Round/Manual

						Difference, Mechanical - Sleeve		CBR, Percent Difference	
Soil Type	Rammer Type	Max Dry Density pcf	Opt Water Content %	CBR @ Sleeve Opt	CBR @ 3% Dry of Sleeve Opt	Max Dry Density	Opt Water Content	Opt	-3%
				Standard Compaction (5.5-lb Rammer)					
CH	Sleeve	100.1	22.2	10.1	14.5				
	Mechanical	100.2	22.1	8.0	10.5	+0.1	-0.1	-21	-28
CL2	Sleeve	108.0	18.6	11.3	24.0				
	Mechanical	108.7	17.8	7.0	15.3	+0.7	-0.8	-38	-36
CL	Sleeve	107.8	17.0	29.5	38.2				
	Mechanical	107.9	17.0	26.0	29.2	+0.1	0.0	-12	-24
SC	Sleeve	125.2	8.2	57.0	58.4				
	Mechanical	125.5	8.1	47.2	51.3	+0.3	-0.1	-17	-12
SM	Sleeve	112.8	11.6	55.5	56.6				
	Mechanical	112.9	11.6	44.4	34.9	+0.1	0.0	-20	-38
				Modified Compaction (10-lb Rammer)					
CH	Sleeve	115.0	15.5	62.0	88.5				
	Mechanical	115.4	15.4	49.5	51.5	+0.4	-0.1	-21	-42
CL2	Sleeve	117.5	14.7	41.0	112.0				
	Mechanical	118.1	14.5	41.0	63.5	+0.6	-0.2	0	-43
CL	Sleeve	113.7	14.3	73.5	60.0				
	Mechanical	112.8	14.7	41.5	23.0	-0.9	+0.4	-44	-62
SC	Sleeve	125.2	4.3	140	142*				
	Mechanical	124.4	3.8	83	85*	-0.8	-0.5	-41	-40*
SM	Sleeve	114.5	11.7	32.0	34.1				
	Mechanical	113.7	11.8	28.5	28.0	-0.8	+0.1	-11	-18

* 1 percent dry of sleeve optimum.

Table 7

Summary of Compaction Calibrations Using Air-Dry Soil

			Wet Density			Dry Density		
Soil Type	Rammer Type	No. Trials	Average pcf	Deviation From Avg pcf	Percentage of Manual Value	Average pcf	Deviation From Avg pcf	Percentage of Manual Value
CH	Manual Sleeve	4	106.2	+0.4/-0.5	100	99.8	+0.4/-0.6	100
	Mech @ 12 in.	3	104.8	+0.2/-0.1	98.7	98.4	+0.2/-0.1	98
	Mech @ 12.8 in.	3	106.3	+0.7/-0.7	100.1	100.4	+0.7/-0.8	100.6
CL2	Manual Sleeve	3	100.8	+0.5/-0.7	100	96.2	+0.5/-0.7	100
	Mech @ 12 in.	3	100.9	+0.2/-0.2	100.1	95.8	+0.3/-0.2	99.6
	Mech @ 12.8 in.	3	100.3	+0.4/-0.3	99.5	95.9	+0.4/-0.4	99.7

Table 8

Summary of Calibration Trials Using
Lead Cyliners in ASTM Apparatus

		Deformation, 10^{-3} in.		Range Above/Below Average	
Rammer Type	No. Trials	Average	Range	10^{-3} in.	Percent
5.5-lb sleeve	10	173.3	170-177	3.7/3.3	2.1/1.9
Mech @ 12 in.	10	137.6	130-144	6.4/7.6	4.7/5.5
Mech @ 12 in.	10	153.9	147-160	6.1/6.9	4.0/4.5
5.5-lb sleeve	10	174.8	173-177	2.2/1.8	1.3/1.0
5.5-lb slotted	10	179.6	174-185	5.4/5.6	3.0/3.1
New 5.5-lb sl wt	10	135.1	123-157	21.9/12.1	16.2/9.0
Mech @ 12 in.	10	159.2	155-164	4.8/4.2	3.0/2.6
Mech @ 12.8 in.	10	173.2	159-178	4.5/14.5	2.6/8.4
5.5-lb sleeve	5	176.0	175-177	1.0/1.0	0.6/0.6
Mech @ 12.8 in.	6	167.8	161-172	4.2/6.8	2.5/4.1
5.5-lb sleeve (5-deg tilt)	5	168.2	165-170	1.8/3.2	1.1/1.9
5.5-lb sleeve	5	172.8	165-178	5.2/7.8	3.0/4.5

Table 9

Summary of Calibration Trials Using Lead Cylinders in Simplified Apparatus

Rammer Type	No. Trials	Deformation, 10^{-3} in. Average	Deformation, 10^{-3} in. Range	Range Above/Below Average 10^{-3} in.	Range Above/Below Average Percent
5.5-lb sleeve	5	184.4	183-188	3.6/1.4	2.0/0.8
5.5-lb new sl wt	5	175.8	174-179	3.2/1.8	1.8/1.0
Mech @ 12 in.	5	184.4	179-187	2.6/5.4	1.4/2.9
Mech @ 12 in.	5	183.4	181-186	2.6/2.4	1.4/1.3
Mech @ 12.8 in.	5	192.6	191-195	2.4/1.6	1.2/0.8
5.5-lb sleeve	5	181.2	179-185	3.8/2.2	2.1/1.2
Mech @ 12.8 in.	5	188.4	184-192	3.6/4.4	1.9/2.3
5.5-lb new sl wt	5	174.8	173-176	1.2/1.8	0.7/1.0
5.5-lb sleeve @ 11-in. drop	5	173.2	168-179	5.8/5.2	3.3/3.0
10-lb sleeve	5	339.0	336-343	4.0/3.0	1.2/0.9
10-lb new sl wt	5	323.6	321-325	1.4/2.6	0.4/0.8
10-lb sleeve @ 15-in. drop	5	304.4	300-308	3.6/4.4	1.2/1.4
5.5-lb sleeve (5-deg tilt)	5	180.8	179-182	1.2/1.8	0.7/1.0
5.5-lb new sl wt (5-deg tilt)	5	170.4	167-176	5.6/3.4	3.3./2.0

Table 10

Summary of Calibration Trials Using Rubber Cylinder Device

Rammer Type	No. Trials	Deformation, 10^{-3} in.		Range Above/Below Average	
		Average	Range	10^{-3} in.	Percent
5.5-lb sleeve	5	402.2	400-405	2.8/2.2	0.7/0.5
Mech @ 12 in.	5	399.8	394-404	4.2/5.8	1.1/1.5
Mech @ 12.8 in.	5	415.4	411-423	7.6/4.4	1.8/1.1
5.5-lb sleeve	5	429.6	413-434	4.4./16.6	1.0/3.9
5.5-lb sleeve	5	411.8	405-419	7.2/6.8	1.7/1.7
5.5-lb new sl wt	5	400.0	374-420	20.0/26.0	5.0/6.5
Mech @ 12 in.	5	399.8	397-403	3.2/2.8	0.8/0.7
Mech @ 12.8 in.	5	414.6	406-420	5.4/8.6	1.3/2.1
5.5-lb new sl wt	6	427.7	372-506	78.3/55.7	18.3/13.0
5.5-lb sleeve @ 11-in. drop	5	390.8	385-399	8.2/5.8	2.1/1.5
10-lb sleeve	5	646.4	641-652	5.6/5.4	0.9/0.8
10-lb new sl wt	5	619.6	616-623	3.4/3.6	0.5/0.6
10-lb sleeve @ 15-in. drop	5	586.6	582-594	7.4/4.6	1.3/0.8

Table 11

Summary of Calibration Trials Using Load Cell

	No.	Peak Force, lb		Range Above/Below Average	
Rammer Type	Trials	Average	Range	10^{-3} in.	Percent
5.5-lb sleeve	6	1650	1550-1700	50/100	3.1/6.1
5.5-lb new sl wt	5	1650	1600-1750	100/50	6.1/3.0
5.5-lb slotted	5	1790	1700-1900	110/90	6.1/5.0
Mech @ 12 in.	5	1184	1160-1200	16/24	1.4/2.0
Mech @ 12.8 in.	5	1267	1150-1300	33/117	2.6/9.2
5.5-lb sleeve	5	1690	1570-1840	150/120	8.9/7.1
5.5-lb new sl wt	5	1504	1440-1610	106/64	7.0/4.3
Mech @ 12 in.	5	1184	1160-1200	16/24	1.4/2.0
Mech @ 12.8 in.	5	1238	1180-1300	62/58	5.0/4.7
5.5-lb sleeve	5	1628	1580-1650	22/48	1.4/2.9
5.5-lb sleeve @ 11 in. drop	5	1594	1490-1670	76/104	4.8/6.5
10-lb sleeve	5	4080	3950-4150	70/130	1.7/3.2
10-lb sleeve @ 15-in. drop	5	3500	3400-3700	200/100	5.7/2.9
10-lb new sl wt	5	3790	3700-3950	160/90	4.2/2.4

Table 12

Summary of Results Using Calibration Devices

	Data for Individual Calibrations				Data from Averaging Calibrations		
Rammer Type	No. Trials	Average of Trials	Range as Percent of Avg	Meets Sample Range Criterion	Average	Range as Percent of Avg	Percentage of 5.5-lb Sleeve Value
Lead Cylinders in ASTM Apparatus (Values in 10^{-3} in.)							
5.5-lb sleeve	10	173.3	4.0	Yes	174.2	1.8	100
	10	174.8	2.3	Yes			
	5	176.0	1.1	Yes			
	5	172.8	7.5	No			
5.5-lb new sl wt	10	135.1	25.2	No	--	--	77.6
Mech @ 12 in.	10	137.6	10.2	Yes	150.2	14.4	86.2
	10	153.9	8.4	Yes			
	10	159.2	5.7	Yes			
Mech @ 12.8 in.	10	173.5	11.0	Yes	170.6	3.3	97.9
	10	167.8	6.6	Yes			
Lead Cylinders in Simplified Apparatus (Values in 10^{-3} in.)							
5.5-lb sleeve	5	184.4	2.7	Yes	182.8	1.8	100
	5	181.2	3.3	Yes			
5.5-lb new sl wt	5	175.8	2.8	Yes	175.3	0.6	95.9
	5	174.8	1.7	Yes			
Mech @ 12 in.	5	184.4	4.3	Yes	183.9	0.5	100.6
	5	183.4	2.7	Yes			
Mech @ 12.8 in.	5	192.6	2.1	Yes	190.5	2.2	104.2
	5	188.4	4.2	Yes			
Rubber Cylinder Device (Values in 10^{-3} in.)							
5.5-lb sleeve	5	402.2	1.2	Yes	414.5	6.6	100
	5	429.6	4.9	Yes			
	5	411.8	3.4	Yes			
5.5-lb new sl wt	5	400.0	11.5	No	413.8	6.7	99.8
	6	427.7	31.5	No			
Mech @ 12 in.	5	399.8	2.5	Yes	399.8	0.0	96.5
	5	399.8	1.5	Yes			
Mech @ 12.8 in.	5	415.4	2.9	Yes	415.0	0.2	100.1
	5	414.6	3.4	Yes			
Load Cell (Values in lb)							
5.5-lb sleeve	6	1650	9.1	No	1656	3.7	100
	5	1690	16.0	No			
	5	1628	4.3	Yes			
5.5-lb new sl wt	5	1650	9.1	No	1577	9.3	95.2
	5	1504	11.3	No			
Mech @ 12 in.	5	1184	3.4	Yes	1184	0.0	71.5
	5	1184	3.4	Yes			
Mech @ 12.8 in.	5	1267	11.8	No	1252	2.3	75.6
	5	1238	9.7	No			

Table 13

Data Used for Statistical Analysis of Lead Cylinders in ASTM Apparatus

Rammer Type	Sample Size n	Sample Mean, $\bar{x}$ 10^{-3} in.	Sample Std. Dev. 10^{-3} in.	Sample Range, R 10^{-3} in.	R/d_2*	Meets Range Criterion
			Durham and Hale Data (1977)			
5.5-lb sleeve	8	166.4	5.80	15	5.27	Yes
	45	172.9	9.92	40	--	Yes
	10	173.0	5.19	14	4.55	Yes
	11	176.2	5.23	16	5.05	Yes
All trials combined	74	172.7	8.43	40	--	Yes
Soiltest Mech. @ 12.6-in. drop	5	170.6	1.52	4	1.72	Yes
	7	158.3	5.15	15	5.55	Yes
	11	167.5	4.70	15	4.73	Yes
Rainhart Mech.	5	142.0	8.37	18	7.74	No
Rainhart Mech. (0.70-lb added)	5	168.4	1.14	3	1.29	Yes
	5	169.8	2.59	6	2.58	Yes
Hogentogler Mech.	6	171.2	2.23	6	2.37	Yes
	7	169.0	1.91	5	1.85	Yes
			Present Study			
5.5-lb sleeve	10	173.3	2.54	7	2.27	Yes
	10	174.8	1.55	4	1.30	Yes
	5	176.0	1.00	2	0.86	Yes
	5	172.8	5.21	13	5.59	No
All trials combined	30	174.2	2.82	13	--	Yes
Soiltest Mech. @ 12.0-in. drop	10	137.6	4.09	14	4.55	Yes
	10	153.9	4.20	13	4.22	Yes
	10	159.2	3.33	9	2.92	Yes
Soiltest Mech. @ 12.8-in. drop	10	173.5	5.64	19	6.17	Yes
	6	167.8	4.36	11	4.34	Yes
Sleeve (5-deg tilt)	5	168.2	2.49	5	2.15	Yes
5.5-lb slotted	10	179.6	2.76	11	3.57	Yes
5.5-lb new sl-wt	10	135.1	11.56	34	11.00	No

* Estimate of sample standard deviation based on range. See Table 14 for values of d_2.

Table 14

Results of Statistical Calculations for Calibration Trials

n*	ν	$t_{0.05}$	$t_{0.01}$	C	s	d_2	$d_2\sigma$	R_{max}	R_{max}, %
2	2	2.920	6.965	4.43	1.52	1.128	1.7	2	1.0
3	4	2.132	3.747	5.44	3.12	1.693	5.3	5	3.0
4	6	1.943	3.143	5.73	4.17	2.059	8.6	9	4.9
5	8	1.860	2.896	5.87	4.99	2.326	11.6	12	6.7
6	10	1.812	2.764	5.94	5.68	2.534	14.4	14	8.3
7	12	1.782	2.681	5.99	6.29	2.704	17.0	17	9.8
8	14	1.761	2.624	6.02	6.84	2.847	19.5	19	11.2
9	16	1.746	2.583	6.05	7.35	2.970	21.8	22	12.6
10	18	1.734	2.552	6.07	7.83	3.078	24.1	24	13.8
11	20	1.725	2.528	6.08	8.27	3.173	26.2	26	15.1
12	22	1.717	2.508	6.10	8.70	3.258	28.3	28	16.3
13	24	1.711	2.492	6.11	9.10	--	--	--	--
14	26	1.706	2.479	6.11	9.48	--	--	--	--
15	28	1.701	2.467	6.12	9.86	--	--	--	--
20	38	1.687	2.430	6.15	11.52	--	--	--	--

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* Key to column headings:

n = sample size

ν = degrees of freedom for t distribution

$t_{0.05}$, $t_{0.01}$ = values of t statistic at 0.05 and 0.01 confidence levels

s = maximum sample standard deviation that will satisfy criteria for give sample size, n

d_2 = constant for sampling distribution of the range, from tables

R_{max} = maximum allowable range for given sample size

R_{max}, % = $d_2\sigma$, expressed as a percent of $\overline{x}$