Notes on the Corps of Engineers' CBR Design Procedure

CHARLES R. FOSTER, Chief, Flexible Pavement Branch; and
R. G. AHLVIN, Chief, Special Projects Section; Flexible Pavement Branch, Soils Division, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

This paper begins with the requirements of a design method and attempts to explain the Corps of Engineers' adoption and use of the CBR design procedures. Background history of the development of these procedures is included and an idea of the magnitude of the supporting research program is conveyed. Details as to the present capabilities of the CBR design method are given and alternate design procedures are briefly discussed. In an appendix the CBR procedures are summarized as to basic concept.

●THE CALIFORNIA BEARING RATIO (CBR) design procedures as practiced by the Corps of Engineers are the primary concern of this paper; however, it is believed desirable to point out that the Corps of Engineers' flexible pavement design procedure embodies two features which deal with the pavement structure and a third which deals with the bituminous mixture. These are as follows:

1. Each layer must be thick enough to distribute the stresses induced by traffic so that when they reach the underlying layer they will not overstress and produce shear deformation in the underlying layer. The CBR procedures are used for determining the thickness required to prevent shear deformation in the underlying layer. This paper is concerned primarily with this problem, which is termed "thickness design."
2. Each layer must be compacted adequately so that traffic does not produce an intolerable amount of added compaction. The modified AASHO laboratory compaction test and construction specifications requiring the proper percentage of laboratory density are used to design against consolidation under traffic.
3. The flexible pavement must have a wear- and weather-resistant medium as a surface that will not displace under traffic. The Corps of Engineers' design procedures using the Marshall stability test are used to design the bituminous paving mixtures to produce a wear- and weather-resistant surfacing that will not displace under traffic.

The basic concepts of a thickness design procedure adapted to the Corps' uses should be noted. These are:

1. The designs must be based on laboratory tests because extensive field test sections are not feasible, particularly in the theater of operations.
2. The designs must be based on procedures which simulate prototype conditions. Samples must be compacted to prototype density and adjusted to future moisture conditions before being subjected to tests. It should be noted that a thickness design procedure has two basic parts: (a) determining the protective thickness required for a soil with a given CBR value, and (b) estimating the CBR the soil will develop after it has been placed in the pavement system and the moisture content has become adjusted to the weakest condition.

CBR DESIGN PROCEDURES

The CBR design procedures have been described in detail elsewhere (1). Briefly, the procedures consist of determining the CBR of the material to be used in a given layer and the application of the CBR to design curves to determine the thickness required above the layer to prevent shear deformation in the given layer during prototype traffic.

The CBR test is conducted by forcing a 2-in. diameter piston into the soil. The load required to force the piston into the soil 0.1 in. (sometimes 0.2 in.) is expressed as a percentage of the standard value for the same penetration in crushed stone. The test can be performed on samples compacted in test molds, on undisturbed samples, or on material in place. The test should be made on material in a state which represents the prototype condition that will be most critical from a design standpoint.

The CBR design procedures as currently used by the Corps of Engineers and the thickness design curves for single-wheel loads, 100-psi tires, are given in the Appendix.

ORIGINAL ADOPTION

The adoption of the CBR method of thickness design for flexible pavements is discussed by McFadden and Pringle(1). They state that during the latter part of 1940 the responsibility for design and construction of military airfields was assigned to the Corps of Engineers. It soon became apparent that a uniform method of thickness design was needed. Several methods then in vogue were based on the bearing capacity of the subgrade as measured by plate-bearing tests. In order to evaluate the use of the plate-bearing test in determining subgrade bearing capacity, special field investigations were made at Langley Field (Va.), Bradley Field (Conn.), and on a Virginia highway test section. The results of these investigations indicated that:

1. The length of time required to develop a satisfactory plate-bearing test procedure would preclude its use in the war emergency program then being faced.
2. In the field plate-bearing test, the proper deflection to determine the "bearing capacity" depends on the basic assumptions in the formula and varies according to combinations of many factors.
3. In most cases, the results of the plate-bearing test would not be applicable to the soil-moisture conditions expected ultimately to develop below a pavement, and it would be difficult to develop a satisfactory method for adjusting the test results to the various moisture conditions.

Methods based on plate-bearing tests made on the surface of the pavement also were studied. Field tests led to the conclusion that the same factors which must be considered in using the test for subgrades must also be considered for tests on the pavement. In addition, the compressibility of the base and pavement entered the problem, and it is practically impossible to differentiate between the deflection due to shear deformation and that due to compression.

From these studies it was definitely concluded that adaptation of an empirical method that had been proved for highway loading was the best solution. This decision narrowed the field and, after some months of investigation of suggested methods, the principles used by the California Highway Department in designing flexible pavements for highway loading, known as the CBR method, were adopted tentatively. The controlling reasons for the adoption were many. Among these reasons were the following:

1. The CBR method had been correlated to the service behavior of flexible pavements and construction methods and successfully used by the State of California for a number of of years.
2. It could be more quickly adapted to airfield pavement design for immediate use than any other method.
3. It was thought to be as reasonable and as sound as any of the other methods investigated.
4. Two states were known to have methods of a similar nature that had been successful.
5. The CBR could be obtained with simple portable equipment either in the laboratory or in the field.
6. Testing could be done on samples of soil in the condition representative of the future moisture condition under most pavements.

DEVELOPMENT OF CBR METHOD FOR AIRFIELDS

In 1942, O. J. Porter, George Bertram, the late T. A. Middlebrooks, and Arthur Casagrande assembled in the Office of the Chief of Engineers, in Washington, D. C., at the request of engineers of the Airfields Branch, OCE, to extrapolate the existing CBR design curves for 7,000- and 12,000-lb wheel loads to wheel loads of 60,000 lb. These men drew upon their knowledge of soils and pavement requirements and prepared design curves which later experience has proved to be remarkably good.

Work began almost immediately on the verification of these extrapolations and on studies leading to the improvement of the CBR test procedures. Initially, the work was assigned by the Airfields Branch, OCE, to the various district offices of the Corps and to the Waterways Experiment Station. After the initial rush of work was out of the way, the Airfields Branch developed well-planned procedures for operating the investigational program which included written long-range and short-range programs, written plans of tests, annual review of programs by a board of consultants, and frequent review of the program with responsible engineers in the Air Force. The requirements for airfield pavements have been constantly increasing due to increased loads and tire pressures and the investigational program has been concerned with providing design criteria to meet these increased requirements. Engineers of the Airfields Branch, OCE, who have been closely associated with this work are Gayle McFadden, T. B. Pringle, R. M. Haines, and F. B. Hennion. F. L. Meara of the U. S. Air Force and S. J. Buchanan, consultant to the U. S. Air Force, have assisted with the reviews. The programs have included the following:

1. Accelerated traffic tests to verify the CBR design curves for single wheels.
2. Study of CBR test procedures.
3. Investigation of failed and satisfactory airfield pavements and comparison of results with design criteria.
4. Development of a more rational method of thickness design.
5. Extension of design procedures to multiple-wheel assemblies and high-pressure tires.
6. Effect of load repetitions.

A board of consultants was retained and assembled at regular intervals to review the investigational programs and to assist in analyzing the test data. The consultants have been outstanding individuals in the fields of soil mechanics, highways, and airfields. Those retained to review the investigational program as a whole included Authur Casagrande, R. E. Fadum, J. L. Land, T. A. Middlebrooks (deceased), O. J. Porter, R. B. Peck, P. C. Rutledge, D. W. Taylor (deceased), H. M. Westergaard (deceased), and K. B. Woods. Assisting in various phases of the program are R. A. Barron, G. E. Bertram, D. M. Burmister, M. J. Hvorslev, N. M. Newmark, Gerald Pickett, and R. R. Philippe. Some of the consultants are from within the Corps of Engineers' organization.

In 1943 the Office of the Chief of Engineers established the Flexible Pavement Laboratory at the Waterways Experiment Station. The investigational program on thickness design has been the responsibility of this laboratory, although some of the test sections have been constructed elsewhere. Engineers who have had major responsibilities in connection with the thickness design programs at the Flexible Pavement Laboratory have been W. J. Turnbull, W. H. Jervis, W. K. Boyd, J. B. Eustis, S. J. Johnson, W. G. Shockley, and C. R. Foster.

The studies that have been conducted for the development and improvements of the thickness design procedures and the major findings are summarized briefly.

Accelerated Traffic Tests

As noted previously, immediately following the extrapolation of the 7,000- and 12,000-lb design curves to curves for higher loadings, a series of accelerated traffic tests was initiated to validate the extrapolations. Special test sections were built at Stockton Field, Calif. (2, 3), Barksdale Field, La. (4), Eglin Field, Fla. (5), and Langley Field, Va. (6), and subjected to accelerated traffic with wheel loads up to

50,000 lb, which was the limit of the available equipment. Accelerated traffic tests also were conducted on existing pavements at eight airfields (7). In 1945 and 1946, a second test section was constructed at Stockton Field and subjected to traffic with wheel loads up to 200,000 lb (8). Tire pressures were generally 100 psi or less, except for the heaviest loads at Stockton No. 2. These studies permitted comparisons between the thickness design curves and the performance under traffic. It should be noted that the comparisons were based on the in-place CBR that existed during the traffic period. As mentioned previously, the problem of developing a design procedure is two-fold. One aspect is determining the thickness required over a soil with a given CBR; the other, is estimating the CBR that a soil will have in prototype conditions. The accelerated traffic tests provided information for only the first part of the program. The comparisons for wheel loads up to 50,000 lb are given by Foster in the CBR symposium (1). He shows that the results were in good agreement for loads below 30,000 lb, but the data indicated that additional thicknesses in the order of 4 to 5 in. were needed for the heavier loads. The results of the Stockton No. 2 data, together with results of behavior of pavements at actual airfields and theoretical studies, were used to make adjustments in the single-wheel load curves which included the increases for the heavier loads. These curves, shown in Figure 43 of the CBR symposium (1), were placed in the July 1951 issue of the "Engineering Manual for Military Construction" (9), and have been used since then with no significant changes. It is considered that the design curves for the single-wheel loads at tire pressures of 100 psi and less are adequately validated, and no accelerated traffic tests have been made for single-wheel loads and tire pressures of 100 psi since the Stockton No. 2 tests.

CBR Test Procedures

As mentioned earlier, one of the first investigations made after adoption of the CBR design method was a comprehensive study of the procedures for preparing samples for the laboratory test and for conducting the penetration test. This study was made at the Waterways Experiment Station and was reported in 1945 (10). One outstanding result of the study was the procedure for compacting samples at a range of compactive efforts and water contents and the plotting of the CBR results to show the variation of CBR with density for equal values of molding water content. These procedures permit a more realistic estimate of the CBR that will develop in the prototype than is possible with any other method. The procedures are described in more detail in the Appendix.

The testing procedures that were developed as a result of the Waterways Experiment Station study (10) were included in the 1946 issue of the Engineering Manual and have been used since that time with only minor modifications. The procedures work well for fine-grained soils, but the laboratory CBR obtained on gravelly soils tends to be higher than is developed in the prototype. The difference is due to the processing that is necessary when material occurs in excess of $^3/_4$-in. maximum size, and to the effect of the mold. Studies have been made of these problems, but no satisfactory test procedures have been developed. To produce satisfactory designs, the CBR test procedures for coarse-graded materials are being supplemented by gradation and Atterberg limits requirements for CBR design values above 20. These supplementary requirements are explained in the Appendix.

Surveillance Studies

Because the real proof of a design procedure is the performance of pavements designed by the procedure under actual traffic, the Flexible Pavement Laboratory has made numerous investigations of pavements at airfields. Failed pavements have been investigated to determine the reason for failure and to obtain a comparison with the behavior and the design criteria. Satisfactory pavements receiving heavy traffic have been investigated for a comparison of existing conditions with the design criteria. Foster (1) presents data collected through 1949 in this study. In general, the results show that the thickness criteria are satisfactory, and in many cases conservative. Field investigations of failed and satisfactory pavements have been continued throughout the years and show the same trend; more are planned for the future.

Rational Design

From the outset, the consultants were of the opinion that the design procedures for flexible pavements would have to be, initially at least, empirical in nature. Some of the consultants doubted that it would ever be possible to develop a truly rational design procedure because of the complexity of the problem, but all agreed that the problem should be studied. Pressure cells and deflection gages were installed in the early test sections and theoretical computations of pressures were made at the Waterways Experiment Station. After a study of these data, the Flexible Pavement Laboratory recommended in 1945 a stress-distribution study which had as its basic purpose the development of a more rational method of flexible pavement design. The requirements for a truly rational design have been established, as follows:

1. Compute the stresses (or strains) induced in a given layer.
2. Submit this layer to a test to measure its true ability to resist the stresses (or strains).
3. Compare stress (or strain) resisting ability with induced stress and express the comparison as a ratio or a factor of safety.

It should be noted that the rather severe problem of how to compact a soil to its future prototype density and adjust the water content to a future weakened condition must be considered in the rational method or in any other method.

Two carefully instrumented test sections (one a sand, the other a clayey silt) have been constructed at the Waterways Experiment Station and subjected to loads over a wide range of conditions. Soil conditions in each were homogeneous. The results (11, 12) show that measured stresses agree closely with those computed using theory of elasticity for low loadings, but show deviations from theory for high loadings. The deviations were greater for the sand than for the clayey silt. Instrumentation difficulties were suspected in the tests made in sand, and recent studies have been concerned primarily with the accuracy of the measurements.

Samples of the soil from the two test sections were subjected to laboratory triaxial tests, and the laboratory stress-strain curves were compared with field stress-strain curves. A significant feature of these tests is that the field stress-strain curves obtained in these studies are believed to be the first ever obtained. The laboratory stress-strain curves obtained from the standard triaxial test showed wide deviation from the field curve. Experimental procedures were tried, and reasonable agreement between the laboratory and field stress-strain curves was obtained by duplicating in the laboratory the relation of vertical to lateral stress that had been measured in the field. Because, however, relationship of vertical to lateral stress is not known, except for the two soils tested, this procedure has little application at present. Future plans include the construction and testing of layered systems. The results will be compared with values computed by Burmister's layered theory (13) for possible validation or modification of the theory.

In addition to the tests previously described, numerous computations of theoretical stresses and deflections were made. One item of particular importance developed from these studies was the finding that the CBR design curves for CBR values below about 20 had a pattern similar to that exhibited by the load, depth, and stress relationship of the theory of elasticity. Fergus (1) showed that the CBR design curves for a given tire pressure could be expressed as $k = \sqrt{\frac{z}{P}}$, where z is depth, P is total load, and k is a constant depending on the CBR value. This relationship has been studied further and improved over the years. It has been of inestimable help in the development of the thickness design curves, as it has permitted comparison of service behavior data for a wide range of wheel loads on one plot as shown in Figure 40 of the CBR symposium (1) and has aided in adjusting the curves to obtain the best possible agreement with the data. Relationships similar to these have been used in adjusting the design curves to other tire pressures and for multiple gear configurations as discussed subsequently.

In summary, the status of the rational design studies is as follows:

1. Induced stresses can be computed for homogeneous sytems with a fair degree of accuracy; the degree of accuracy would probably be satisfactory for cohesive materials, but not for cohesionless materials.
2. Triaxial tests as usually run do not measure true stress-strain relationships. Triaxial tests can be run which duplicate field stress-strain conditions for the cases where the stress-strain conditions are known. Universal procedures for the tests have not been developed.

Although the stress distribution studies have not as yet produced a rational design method, they have produced the means for translating the single-wheel design curves into curves for other conditions of loadings. The studies have also permitted evaluation of the several so-called "rational" design procedures that have been proposed in the technical literature.

Multiple Wheels and High-Pressure Tires

The growth of aircraft during the latter part of World War II and subsequently has led to the development of multiple-wheel assemblies and high-pressure tires by the aircraft designers. A test section to compare the effects of the dual-wheel assembly used on the B 29 aircraft with a single-wheel assembly of equal load was constructed at Marietta, Ga. (14). The results were used to develop design curves for the B 29 aircraft. Subsequent study produced theoretical procedures for resolving the single-wheel curves into curves for multiple-wheel assemblies. These procedures are described by Foster and Boyd in the CBR symposium (1). The Stockton No. 2 test section also included limited study of multiple-wheel assemblies. In 1949 and 1950, a test section was constructed at the Waterways Experiment Station to verify the theoretical resolutions of single-wheel curves into multiple-wheel curves. These tests (15) indicated that the theoretical procedures gave thicknesses which were slightly unconservative. A complete reanalysis (16) of all data resulted in a more rational method of developing multiple-wheel design curves by adjusting the thickness for a given multiple-wheel load on a given subgrade to produce a deflection in the subgrade equal to that produced by the load when carried on a single wheel. The curves produced in this manner are in good agreement with the traffic test section data. It should be noted that this theoretical treatment stemmed from the rational design studies.

A similar procedure was used to adjust thickness requirements for high-pressure tires. Test sections (17) were constructed in 1949-1951 at the Waterways Experiment Station to check these procedures. The tests included tire pressures in the range of 200 psi and, as a result of these studies, the design curves are considered adequate for tire pressures up to 200 psi.

Effect of Repetitions

In the theater of operations, the thickness must be limited to that barely necessary to support the operation. Therefore, design criteria were needed for limited usage. A study of available data developed a relationship between volume of traffic and the percentage of full design thickness necessary to support the traffic. This concept is presented in Figure 41 of the closure paper to the CBR symposium (1). Improvement and modification of the concept have permitted the development of thickness design criteria for the following operations:

Type	Nominal Duration	Nominal Coverages
Assault	1 day	6
Emergency	2 weeks	40
Minimum	6 months	700
Full	2 years	2,000
Capacity	More than 10 years	5,000
Channelized	More than 10 years	30,000

Field Moisture Studies

Pavements must be designed not merely for the subgrade strength existing at the time of construction, but for the worst conditions expected in the future. Therefore, some evaluation of these future conditions is necessary. The CBR procedures make use of tests on soaked samples to take care of this condition. In February 1945 the Flexible Pavement Laboratory undertook a field moisture study which was intended to develop a better understanding of moisture conditions under flexible pavements. Airfields in various climatic zones were visited repeatedly in various seasons and in successive years. Test pits were opened and the necessary samples taken to evaluate mosture, density, and CBR. In addition, moisture cells have been installed in some instances and closely spaced periodic readings made of the field moisture. Results reported through November 1952 (18, 19) show that the 4-day soaking test is conservative for nonplastic or slightly plastic materials, but is about correct or slightly conservative for plastic or very plastic materials.

Present Status of CBR Procedures

In summation, the investigational work accomplished to date has yielded the following results:

1. Thickness design curves. Design curves are available which can be adjusted theoretically to any condition of gear configuration, tire pressure, and repetition. The design curves are validated for a range of tire pressures up to 200 psi, tire loads to 200,000 lb, and repetitions up to 5,000 coverages.
2. Determining prototype strength. Sample preparation and test procedures are available by which materials can be compacted to prototype densities and adjusted to a future condition of water content. When used with fine-grained soils, the procedures give results which are satisfactory or slightly conservative for the plastic materials and are conservative for nonplastic and slightly plastic materials. The procedures have been supplemented by gradation and Atterberg limits tests for gravelly soils.

OTHER DESIGN PROCEDURES

The Flexible Pavement Laboratory has followed closely the technical literature on flexible pavement design and has studied those design procedures which have been used or proposed for use. The Highway Research Board Committee on Flexible Pavement Design has reported (20, 21) on the various design procedures used by the organizations in the United States. These procedures can be grouped into four general categories as follows:

1. Procedures which can use an index based on soil constants or soil classification, such as the Bureau of Public Roads' group index or the CAA rating.
2. Procedures which use a physical test to obtain an index of the strength, such as the North Dakota cone or Florida bearing test.
3. Procedures which use a form of shear test, such as direct shear or triaxial shear.
4. Procedures which use a plate-bearing test.

The first two groups are not discussed further herein.

Shear Tests

The California Division of Highways uses the Hveem Stabilometer method of design (22), which utilizes the strength obtained from a modified triaxial test and a nomograph to obtain thickness. The Kansas method (23) uses a conventional type of triaxial test to measure strength. The problems associated with using a shear test were mentioned briefly earlier under "Rational Design." The major obstacles are the determination of the shearing stress induced in the system by the wheel loading and the determination of the normal stress which will be available to develop strength to resist this shearing stress. In both the Hveem and Kansas methods these problems are bypassed by conducting the strength test at a standardized lateral pressure and comparing designs based on these strengths with service behavior records. This is essentially an empirical procedure. The other procedures employing strength tests use similar methods to overcome the problems mentioned. These empirical procedures are workable, but design methods using them are only as good as the correlations which have been developed to verify the procedures.

Plate-Bearing Tests

In addition to the studies of plate-bearing tests which were made preparatory to adopting the CBR method, extensive plate-bearing tests were conducted in connection with the Barksdale Field test section (4). Also, study has been made of the plate-bearing tests made by the Bureau of Public Roads in its test track at Hybla Valley (report not published), the plate-bearing tests made by McLeod (24), the British Load Classification Number (LCN) System (25), and the Navy design procedure (26). It should be noted that the published correlations between the load required to produce a given deflection and the actual traffic-carrying capacity of the pavements are limited.

It is considered that the plate-bearing test could be used satisfactorily under the following circumstances:

1. The plate-bearing test procedures would have to be modified to produce large deformations (½ to 1 in.) in order to eliminate the effect of consolidation and measure only resistance to shear deformation.
2. The large deformations would require much larger loading equipment than available. At Barksdale Field, a load of approximately 28,000 lb was required to produce 0. 5-in. deformation with a 30-in. diameter plate on a clay subgrade. A load of 50,000 lb on a CBR of 5 did not produce 0. 1-in. deformation on the base course.
3. Correlations would have to be developed between the load at given deflections and actual traffic-carrying capacity.

The plate-bearing procedures have not been adopted by the Corps of Engineers because the correlations required between load predicted by the plate-bearing tests and actual traffic-carrying capacity would be very expensive and no feasible means for adjusting the water content in a full-scale test section could be devised. Also, the Corps of Engineers' contract procedures are such that no assurance could be had that the subbases and bases used in the test sections would be the same as those used in the final construction.

SUMMARY

The Corps of Engineers, after a study of available methods, adopted the CBR procedures for design of flexible pavements. Throughout the years, investigations have been continued to adapt the procedures to the needs of airfields and to the ever-increasing loads and tire pressures of military aircraft. At present, the CBR method is considered superior to other empirical methods because of the extensive correlations which have been developed for the method and because the method has been adapted to include variations in load, gear configuration, tire pressure, repetitions, and climatic conditions.

The engineers in the Corps responsible for this work have recognized the desirability of a more rational method, and investigations have been conducted to develop a more rational method. The work has produced many worth-while by-products, but a truly rational design method is not possible at the present time. Some of the problems may never lend themselves to truly rational treatment.

REFERENCES

1. "Development of CBR Flexible Pavement Design Methods for Airfields—A Symposium." ASCE Trans. 115:453 (1950).
2. "Stockton Runway Test Section." Sacramento District, Corps of Eng., U. S. Army (Sept. 1942).

3. "Supplement to Stockton Runway Test Section." Sacramento District, Corps of Eng., U.S. Army (May 1944).
4. "Service Behavior Test, Barksdale Field, Louisiana." Comprehensive report with five appendixes (July 1944) and published report (Oct. 1944). Little Rock District, Corps of Eng., U.S. Army.
5. "Accelerated Traffic Tests, Eglin Field, Florida." Mobile District, Corps of Eng., U.S. Army (Jan. 15, 1945).
6. "Accelerated Traffic Tests, Langley Field, Virginia." Norfolk District, Corps of Eng., U.S. Army (June 1945).
7. "Summary Report, Accelerated Traffic Tests." Waterways Experiment Station, Corps of Eng. (Feb. 1947). 47).
8. "Accelerated Traffic Test at Stockton Airfield, Stockton, California (Stockton Test No. 2)." 7 vol, Sacramento District, Corps of Eng., (by O. J. Porter and Co., Cons. Eng.) (May 1948).
9. "Engineering Manual for Military Construction." Airfield Pavement, Design, Flexible Pavements. Part XII, Ch. 2 (July 1951).
10. "The California Bearing Ratio Test as Applied to the Design of Flexible Pavements for Airports." T.M. 213-1, Waterways Experiment Station, Corps of Eng. (July 1945).
11. "Investigations of Pressures and Deflections for Flexible Pavements." T.M. 3-323, Report No. 1, Homogeneous Clayey-Silt Test Section, Waterways Experiment Station, Corps of Eng. (Mar. 1951).
12. "Investigations of Pressures and Deflections for Flexible Pavements." T.M. 3-323, Report No. 2, Homogeneous Sand Test Section, Waterways Experiment Station, Corps of Eng. (Dec. 1954).
13. Burmister, D.M., "The Theory of Stresses and Displacements in Layered Systems and Applications to the Design of Airport Runways." HRB Proc., 23:126 (1943).
14. "Certain Requirements for Flexible Pavement Design for B 29 Planes." Waterways Experiment Station, Corps of Eng (Aug. 1, 1945).
15. "Design of Flexible Airfield Pavements for Multiple-Wheel Landing Gear Assemblies." T.M. 3-349, Report No. 1, Test Section with Lean-Clay Subgrade, Waterways Experiment Station, Corps of Eng. (Sept. 1952).
16. "Design of Flexible Airfield Pavements for Multiple-Wheel Landing Gear Assemblies." T.M. 3-349, Report No. 2, Analysis of Existing Data, Waterways Experiment Station, Corps of Eng. (June 1955).
17. "Design of Upper Base Courses for High-Pressure Tires." T.M. 3-373, Report No. 1, Base Course Requirements as Related to Contact Pressure, Waterways Experiment Station, Corps of Eng. (Dec. 1953).
18. "Field Moisture Content Investigation." T.M. 3-401, Interim Report No. 1, Waterways Experiment Station, Corps of Eng. (May 1948).
19. "Field Moisture Content Investigation." T.M. 3-401, Report No. 2, October 1945 - November 1952 Phase, Waterways Experiment Station, Corps of Eng. (Apr. 1955).
20. "Thickness of Flexible Pavements for Highway Loads." HRB Current Road Problems 8-R (1949).
21. "Flexible Pavement Design." HRB Bull. 80 (1953).
22. Hveem, F.N., and Carmany, R.M., "The Factors Underlying the Rational Design of Pavements." HRB Proc., 28:101 (1948).
23. "Design of Flexible Pavements Using the Triaxial Compression Test." HRB Bull. 8 (1947).
24. "Airport Runway Evaluation in Canada." HRB Research Report 4B, Part II, 1948 Supplement (1948).
25. Skinner, J.A., "Testing Runway Foundations and Pavements." Airport Paper No. 17, Proc. Inst. Civil Eng. (1951).
26. "Airfield Pavement." Tech. Publ. NAVDOCKS TP-Pw-4, U.S. Navy, Bur. Yards and Docks (Jan. 1953).

Appendix

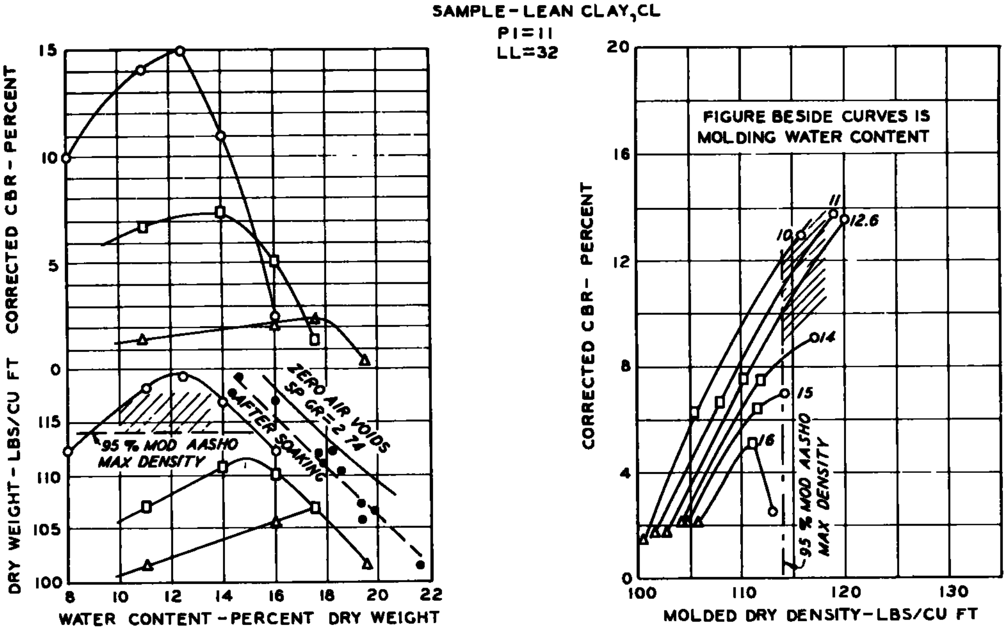
Summary of CBR Procedures Currently Used by the Corps of Engineers

This summary presents the basic concept of the CBR design procedures currently used by the Corps of Engineers; for details, the reader is referred to the current issue of the "Engineering Manual for Military Construction" published by the Office of the Chief of Engineers.

Where new construction is involved, which is the usual case, representative samples of the soils are tested for CBR value in the laboratory. A test program is prescribed which requires compaction of samples in 6-in. diameter test molds at three compactive efforts, approximating modified AASHO compactive effort, standard AASHO compactive effort, and an intermediate effort. Samples are prepared at a range of water contents for each effort. After compaction, the samples are soaked in water for four days under a surcharge load equal to the weight of the overlying base and pavement. After soaking, the samples are tested for CBR.

Basically, the CBR test consists of forcing a 2-in. diameter piston into the soil at a constant rate of 0.05 in. per minute and measuring both the load and the penetration. The load required to produce 0.1-in penetration (sometimes 0.2-in.) is compared to the standard load required to produce the same penetration in crushed stone. The load in the test is expressed as a percentage of a standard load.

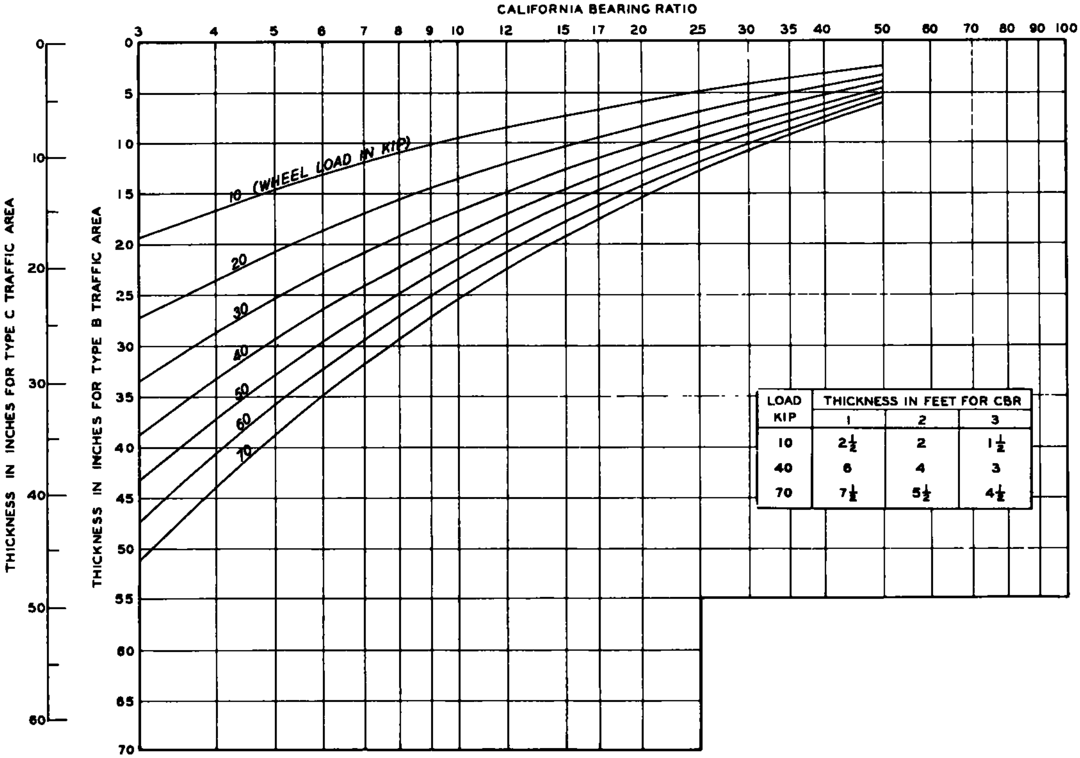
When tests are conducted on samples compacted at a range of compactive efforts and water contents, the results produce a family of curves as shown in Figure 1. This family of curves shows the three-way relationships of molding water content, density, and CBR. These curves are then studied in view of the actual water contents and densities that can be expected in construction. The CBR values that will result from the combinations of water content and density are determined from the test curves, and a design CBR is selected, usually near the lower end of the range in CBR values. The shaded area in Figure 1 illustrates the range of water contents and densities that might



NOTES
(1) SURCHARGE = 10 LBS SOAKING AND PENETRATION
(2) ALL SPECIMENS SOAKED TOP AND BOTTOM FOR 4 DAYS
(3) ALL SPECIMENS COMPACTED IN LAYERS, 10-LB HAMMER, 18-IN DROP IN CBR MOLD

LEGEND
○ 55 BLOWS PER LAYER
□ 25 BLOWS PER LAYER
△ 10 BLOWS PER LAYER
● WATER CONTENT, TOP IN

Figure 1. Recommended procedure for performing CBR tests for design.



LOAD KIP	THICKNESS IN FEET FOR CBR		
	1	2	3
10	2½	2	1½
40	6	4	3
70	7½	5½	4½

Figure 2. Flexible pavement design curves, single wheel, tire inflation 100 psi; types B and C traffic areas.

be expected for the soil tested. The CBR that will develop with this range of water contents and densities will vary from about 7 to 14. A value near the lower end of the range, say 8 or 9, should be used for design in this case.

Experience has shown that laboratory CBR tests on gravelly materials used for high-strength subgrades and subbase courses often show CBR values higher than are obtained in the prototype, primarily because of the confining effect of the mold. The CBR test has been supplemented by gradation and Atterberg limits requirements for gravelly materials as shown in the following table, which gives the gradation and limit values which must be met for the various design CBR values. In addition, the material must show a CBR in the laboratory test equal to or higher than the assigned design value.

	Maximum Permissible Value				
	Max. Size	Gradation Requirements (% passing)		Liquid	Plasticity
Design CBR	(in.)	No. 10	No. 200	Limit	Index
40 - 50	3	50	15	25	5
30 - 39	3	80	15	25	5
20 - 29	3	100	15	25	5

The effects of processing base course materials and the effects of the 6-in. diameter mold in tests on base course materials are so great that laboratory CBR tests are not used for rating base course materials. Instead, arbitrary CBR ratings are assigned to materials meeting certain specification requirements. These ratings have been based on service behavior records and on in-place tests of materials that had been subjected to traffic. As an example, a graded crushed aggregate composed of both crushed-coarse and crushed-fine aggregate meeting relatively strict gradation requirements and having a plasticity index of 5 or less in place has been rated at a CBR of 100 percent. Stabilized-aggregate base, meeting essentially the same requirements except that the fine aggregate does not have to be a crushed material, has been rated at a CBR of 80 percent.

Figure 2 shows the CBR design curves for single-wheel loads and 100-psi tire pressures. The CBR of the soil being considered is applied to Figure 2 to determine the combined thickness of base and pavement. Curves are available for 200-psi tire pressures and for various multiple-wheel assemblies. Two thickness scales are shown in Figure 2; one for type B and one for type C traffic areas. The interior portion of the runway is designated as type C traffic area; the remainder of the airfield is designated as type B.

Discussion

W. H. CAMPEN, Manager, Omaha Testing Laboratories, Omaha, Nebraska — One of the principal points in the author's notes on the use of the CBR test results for purposes of thickness design deals with the elimination of the test for certain mixtures. The reason given for eliminating the test lies in the fact that laboratory results cannot be duplicated in the field. From actual field experience, it is agreed that field results are lower than those in the laboratory. However, the elimination of the test to measure base or subbase quality does not seem warranted.

Mr. Foster and his co-workers will no doubt remember that when the CBR test and its use for the estimation of thickness was proposed in 1942, the writer was in favor of adopting the test for the purpose of measuring quality, but was also very much opposed to its use in determining thickness of superimposed layers. He is of the same opinion now. The CBR test should be made on all subbase and base courses to determine their relative strengths. The indicated strengths should then be considered in determining total thickness on a given subgrade for a given wheel load.

As for the lack of CBR duplication in the field, there is at least one good reason, other than lateral support, why the field test might be lower. In the laboratory the sample has a rigid support in the steel mold base. In the field, however, the support consists of everything below the surface; all the base, subbase, and subgrade. Any consolidation or displacement in the subbase and subgrade would automatically decrease the CBR value in the base and any consolidation or displacement in the subgrade would reduce the CBR of the subbase.

CLOSURE, Charles R. Foster and R. G. Ahlvin — Mr. Campen points out the the laboratory CBR test has been eliminated for certain mixtures. It is desired to emphasize that this has been done only for high-quality base course materials that meet relatively strict gradation requirements and that have plasticity indexes of 5 or less. These materials typically show very high laboratory CBR values and also field CBR values equal to or higher than the design values that are arbitrarily assigned to them by the new procedures. For this reason, it was felt that the laboratory CBR test was no longer needed on these high-type base course materials. For granular materials of lower quality, the CBR test has been supplemented by gradation and limit requirements.

The authors concur with Mr. Campen that the steel base of the mold affects the results, in addition to the lateral support offered by the wall of the mold.