Compactness and Bearing Capacity of Soils in Roads

Compacité et capacité portante des sols de fondations de routes

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SUMMARY

This paper shows that a linear relationship, $\gamma = \gamma_0 + b \log$ C.B.R., exists between the dry density and C.B.R. of a given soil, which passes through point C with co-ordinates $\gamma = 2.30$ gram/cu cm and C.B.R. = 543 per cent. For Angola soils the linear relationship has always been observed, the passage through point C being noted in more than 90 per cent of cases. No cases arose which might reliably indicate that it does not occur, with the exception of monogranular soils or soils of very poor grading.

The C.B.R. values of the Angola soils for the different maximum dry densities obtained in the standard compaction test (γ_n) are shown: C.B.R.$_{np} = K\,(\gamma_n - 1.10) : (2.30 - 1.10)$, K being variable from 5 to 23 in 95 per cent of the cases, with a 11.3 mean value. A method is proposed for predicting the mechanical properties based on γ_n. The dry densities $\gamma = 1.10$ and $\gamma = 2.30$ gram/cu cm seem to constitute the limits of the possible densities of the soils.

SOMMAIRE

On montre dans ce travail qu'il y a une relation linéaire $\gamma = \gamma_0 + b \log$ C.B.R. entre les densités sèches et les valeurs C.B.R. d'un sol, laquelle passe par un point C de coordonnées $\gamma = 2{,}30$ gramme/cm.cu. et C.B.R. = 543 pour cent. Pour les sols d'Angola cette relation linéaire a été toujours vérifiée. Le passage par le point C a été vérifié dans plus de 90 pour cent des cas, et en aucun cas on peut affirmer avec assurance que le point C n'est pas atteint, à l'exception des sols monogranulaires ou de granulométrie très uniforme.

On indique les valeurs C.B.R. des sols d'Angola pour diverses densités sèches maxima obtenues à l'essai de compactage normal (γ_n); C.B.R.$_{np} = K\,(\gamma_n - 1{,}10) : (2{,}30 - 1{,}10)$ où K varie de 5 à 23 dans 95 pour cent des cas, avec une valeur moyenne de 11,3. On propose une méthode pour prédire les propriétés mécaniques basée sur γ_n. Les densités sèches $\gamma = 1{,}10$ et $\gamma = 2{,}30$ gramme/cm.cu. semblent constituer les limites possibles des densités sèches des sols.

CORRELATION BETWEEN DENSITY AND C.B.R.

IN FIG. 1, $\gamma_d = f_1(w)$, γ_d being the dry density, in gram/cu cm and w the per cent moisture content. After drawing the iso-C.B.R. lines (Klein, 1955) in this diagram, two types of curves can be derived: (*a*) C.B.R. = $f_2(\gamma_d)$, w = constant, variable energy; (*b*) C.B.R. = $f_3(w)$, constant compaction energy. In case (*a*) the w = constant, straight line is followed; in case (*b*) a compaction curve is followed.

The function C.B.R. = $f_3(w)$ is useful to indicate to the builder the maximum value of w permissible in construction and is of special interest in countries where the natural soil has a tendency to show $w > w_n$ (w_n being optimum moisture content in the standard compaction test). This case is very rare in Angola, and if it occurs, it is during the period of heavy rainfall.

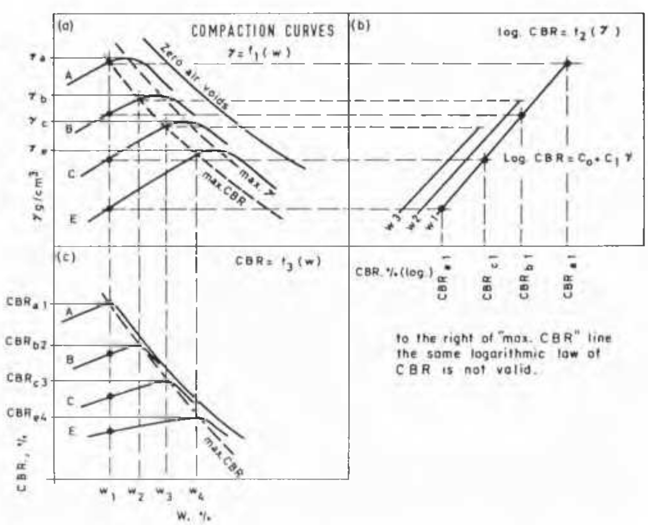

FIG. 1. Type correlation between γ, w, and C.B.R.

The following function relating C.B.R. and γ_d was obtained experimentally (Novais-Ferreira and Crespo, 1957):

$$\log \text{C.B.R.} = C_0 + C_1\gamma_d. \qquad (1)$$

This expression was found to be valid provided that: (1) The moulding moisture content of the specimens was sensibly the same for all specimens ($w \simeq$ const)*; (2) This moisture content was less than the optimum content for the highest compaction energy used (usually that of the A.A.S.H.O. T 180 test, w_m, whereby it should be $w > w_m$); (3) The soaking of the samples leads to approximately the same degree of saturation.

The determination of the function (Eq 1) reported in 1957 was based on 911 soils of nine types (sandy, silty, and clayey). The statistical method as well as the direct method were used. The statistical method showed that the dry densities in the field obey Gauss's law and the C.B.R. in the field obey the log-normal law, whereby Eq 1 is valid. The direct method consisted of tracing, for each soil, the straight lines (1) based on the values (γ_d; C.B.R.) obtained in each test, and of the determination of the correlation of the actual values with those taken from the straight line obtained.

*This same law seems to be observed along the compaction curve, different constants applying to the two branches of the compaction curve. The C.B.R., for equal γ_d, are higher at the ascending branch. In the neighbourhood of $\gamma_{max.}$ a transition curve can be seen joining the two segments of the log C.B.R. = $f_2(\gamma_d)$ straight lines.

Since 1957 the hypothesis of the function (Eq 1) has continued to be tested, and the statistical hypothesis (Campinos, 1959) of the log-normal distribution of C.B.R. has been also confirmed. The samples already tested (exceeding 4,000 in number) have led to the confirmation of hypothesis (1) whenever the three conditions referred to above are satisfied. When they are not satisfied, abnormalities can be seen. Thus, if $w \geqslant w_m$, the function log C.B.R. $- f_2(\gamma_d)$ becomes non-linear, giving low C.B.R. values when γ_d increases. On the other hand if the soaking is small, the C.B.R. values tend to be high. This occurs in impermeable and very compact soils.

The adjustment of the straight line (1) is sometimes difficult when the number of tests is small. Such a difficulty should be attributed to the great dispersion of the C.B.R. tests (Novais-Ferreira, 1962, p. 37). Test errors and excessive moisture content lead to results that do not comply with Eq 1. Every time discrepancies were found, a careful repetition of the tests produced more suitable results. As an example, the results obtained from a single soil are presented in Fig. 2*.

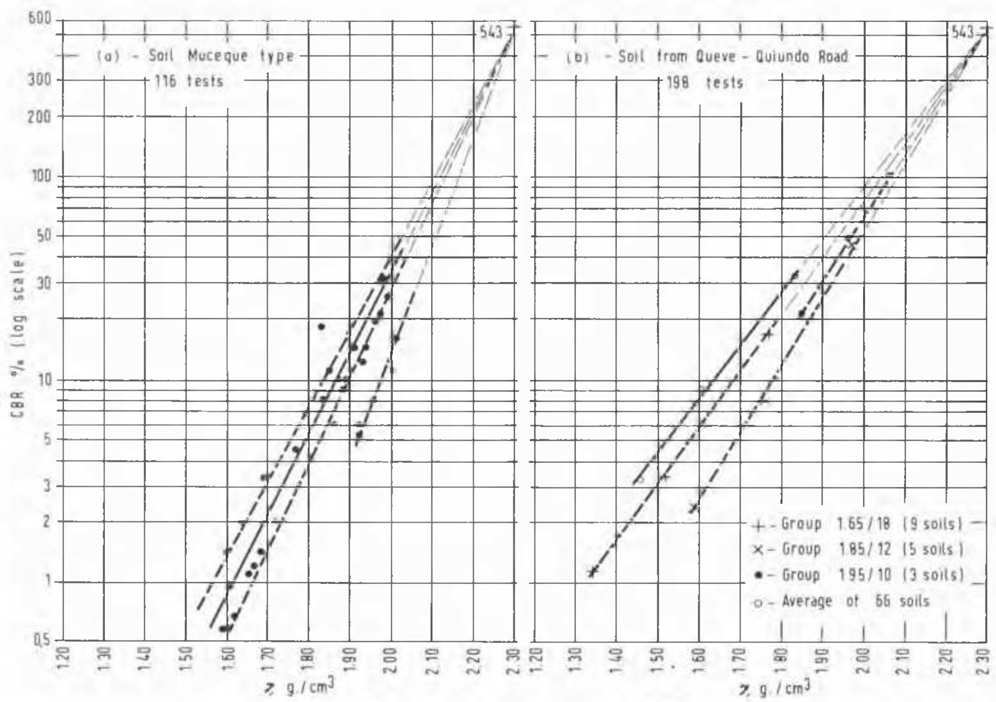

FIG. 2. Correlation between γ and C.B.R.

Subsequent confirmation was also obtained from the means of different soils using the principle that the mean $\bar{y}$ of values of various functions $y_i = a_i + b_i x$ for the same values of x still is a straight line $\bar{y} = \bar{a} + \bar{b}x$. Based on this principle, the C.B.R. values of different soils, with γ_d values differing by less than 0.05 gram/cu cm, have been grouped. In Fig. 2b three examples are presented for soils taken along 30 km of a road, and tested in November, 1963. The general mean of the soils tested from that road is shown in Fig. 2.

Thus Eq 1 appears to be generally applicable to all the soils tested, whenever the three conditions are observed.

*Fig. 2 shows that points following different straight lines but coinciding at one point appear. Each straight line will correspond to a different moisture content as outlined in Fig. 1a.

COMMON POINT

Let us consider Eq 1 in the form:

$$\gamma = a + b \log \text{C.B.R.} \qquad (1a)$$

For C.B.R. = 1, $a = \gamma_0$, γ_0 being the value of γ for log C.B.R. = 0. For C.B.R. = 100, $b = (\gamma_2 - \gamma_0):2$, γ_2 being the value of γ for log C.B.R. = 2. Thus

$$\gamma = \gamma_0 + [(\gamma_2 - \gamma_0)/2] \log \text{C.B.R.} \qquad (2)$$

or

$$\gamma - \gamma_0/\gamma_2 - \gamma_0 = \log \text{C.B.R.}/\log 100. \qquad (3)$$

The values γ_0, γ_2, C.B.R. = 1, and C.B.R. = 100 are not as a rule obtainable in practice, being determined exclusively by graphical or analytical extrapolation. The values γ_0 and γ_2 are characteristic dry densities of each soil.

In order to determine a possible general law for all soils based on Eq 1, straight lines corresponding to those expressions were drawn for 555 of the soils tested. By graphical extrapolation (in most cases) the values of γ corresponding to C.B.R. = 1 per cent (γ_0) and to C.B.R. = 100 per cent (γ_2) were determined. For greater precision the soils were classified according to the value of γ_0, in class intervals of 0.005 gram/cu cm starting from 1.20 gram/cu cm. Thus a soil with the dry density $\gamma_0 = 1.48$ gram/cu cm will fall into the group $1.450 \leqslant \gamma_0 \leqslant 1.499$ gram/cu cm.

Fig. 3 is a variation curve for the mean values of γ_2 with the mean values of γ_0. The correlation between these mean values is rather clear, it being possible to fit the straight line:

$$\gamma_2 = c + d\gamma_0 = 1.68 + 0.269\gamma_0. \qquad (4)$$

Eq 4 further shows that for $\gamma_0 = 2.30$ gram/cu cm $\gamma_2 = \gamma_0$. For values of $\gamma_0 > 2.30$ gram/cu cm, $\gamma_2 < \gamma_0$, which is inadmissible. Eq 4 is only valid, therefore, for $\gamma_0 \leqslant 2.30$ gram/cu cm.

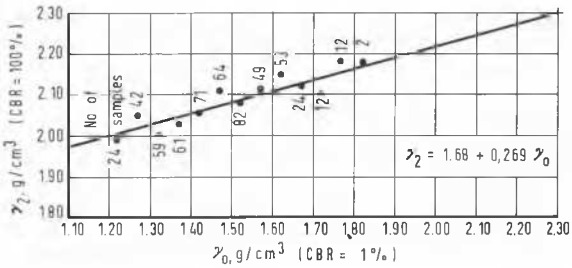

FIG. 3. Correlation between dry densities corresponding to C.B.R. = 1 per cent and C.B.R. = 100 per cent for different soils.

Substituting γ_2 given by Eq 4 in Eq 2 the following equation is obtained:

$$\gamma = c/2 \log \text{C.B.R.} + \left(1 + \frac{d-1}{2} \log \text{C.B.R.}\right)\gamma_0. \quad (5)$$

The values of γ will be independent of γ_0 when

$$1 + (d - 1/2) \log \text{C.B.R.} = 0,$$

that is, when

$$\log \text{C.B.R.}_c = 2/1 - d. \quad (6)$$

Substituting values in Eq 1a, $\gamma_c = 2.30$ gram/cu cm, and C.B.R. = 543 per cent, log C.B.R.$_c$ = 2.7348. These values define a point C common to straight lines (1).

Subsequently the tests of the soils that served as basis for the examination in the previous section were reconsidered. In examining the probable error of the C.B.R. values it was found in graphs of log C.B.R. = $f_2(\gamma_d)$ that: (1) In most cases the orientation of the points defined a straight line passing through point C. (2) When doubt arose, it was possible to draw a straight line passing through C and within the intervals defining the probable limits of the correct C.B.R. value with 95 per cent probability. (3) Only in cases of monogranular soils or soils of very poor grading did the common point C seem to be unacceptable.

The tests done subsequent to 1959 have confirmed these conclusions. As an example, of the results for soils tested from October to December, 1963, corresponding to 90 km of roads may be quoted for 211 soils, and 1,266 tests, 10 straight lines showed a coefficient b less than the normal one and 12 a greater coefficient; that is only 22 straight lines did not pass through point C. Only the tests of two soils were repeated, but in those cases, the repetitions showed that the first tests were wrong* and that the new straight lines passed through point C. It can therefore be stated that the straight lines (1) pass through point C in at least 90 per cent of the cases.

Eq 1a may then take the form

$$\gamma = \gamma_0 + (0.841 - 0.3656\gamma_0) \log \text{C.B.R.} \quad (7)$$

Similarly to Eq 3 it can be shown that

$$\gamma - \gamma_0/2.30 - \gamma_0 = \log \text{C.B.R.}/\log 543. \quad (8)$$

*The non-observance of one or more of the three conditions is usually the cause of the non-confirmation of this rule. Each soil may show more than one straight line (1) (Fig. 1b). When points on two distinct straight lines are found, abnormalities are traced.

or, alternatively,

$$\log \text{C.B.R.} = 2.73(\gamma - \gamma_0/2.30 - \gamma_0). \quad (9)$$

C.B.R. MEAN VALUES AND INFLUENCE OF COMPACTION

Results of tests on 515 and 505 samples were grouped on the basis of the maximum density in the standard and modified compaction tests (γ_n and γ_m), classes of soils being defined in a similar manner to that used above for γ_0. In this way mean C.B.R. values for each group have been obtained, which define two functions: $\overline{\text{C.B.R.}}_{np} = F_{np}(\gamma_n)$ and $\overline{\text{C.B.R.}}_{mp} = F_{mp}(\gamma_m)$ (Figs. 4 and 5).

These F functions have a different character from $f(1)$ because they define the mean C.B.R. of the set of soils of which the maximum density in the standard compaction test is γ. Thus, when a soil presents a maximum density γ_n in the standard compaction test, the most probable C.B.R. will be $\overline{\text{C.B.R.}}_{np}$. Similarly it will be $\overline{\text{C.B.R.}}_{mp}$ in the case of the value of the maximum density γ_m being considered in the modified compaction test. The second series of tests with 573 samples, is also represented in Figs. 4 and 5.

The correlation between maximum densities in the standard and modified compaction tests given by the expression $(1/\gamma_m) = 0.132 + 0.698\ (1/\gamma_m)$ was confirmed, as well as the relation $w_m = 0.804\ w_n$ (Novais-Ferreira, 1963).

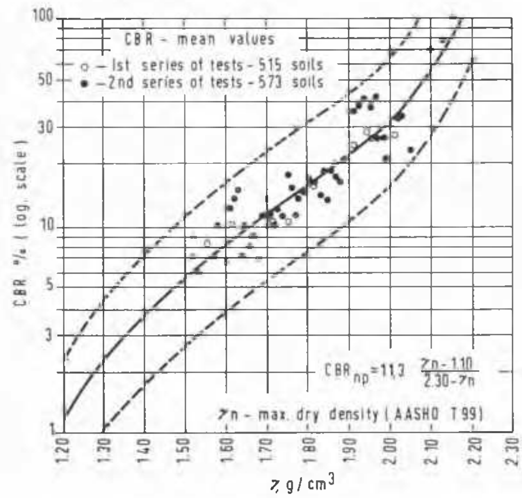

FIG. 4. Relationship of γ_n and probable mean C.B.R.$_n$.

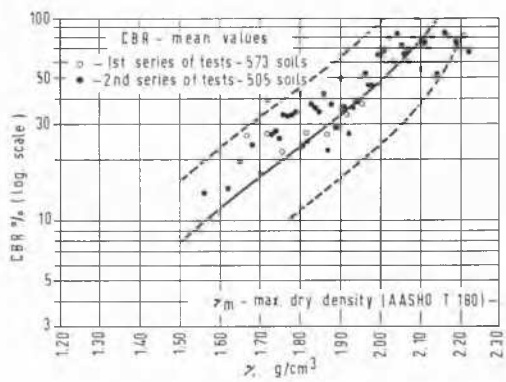

FIG. 5. Relationship of γ_m and probable mean C.B.R.$_m$.

An appreciation of the foregoing permits evaluation of the behaviour of the soils on the basis of the results of the standard compaction test.

In Fig. 6 an example of forecast of C.B.R. (C.B.R.$_{p}$ = C.B.R. expected) is presented in scheme. Since the standard deviation of the C.B.R. is about 2 (Novais-Ferreira, 1962), it is to be expected that the actual C.B.R. (C.B.R.$_{a}$) be contained in the interval [C.B.R. $\times$ $2^{\pm t}$], t being a constant dependent on the probability of values outside the interval (Fisher, *et al.*, 1954; A.S.T.M., 1960). For $t = 1$ the probability of values outside the interval is 32 per cent. Other values of 2^{t} have been given previously (Novais-Ferreira, 1962).

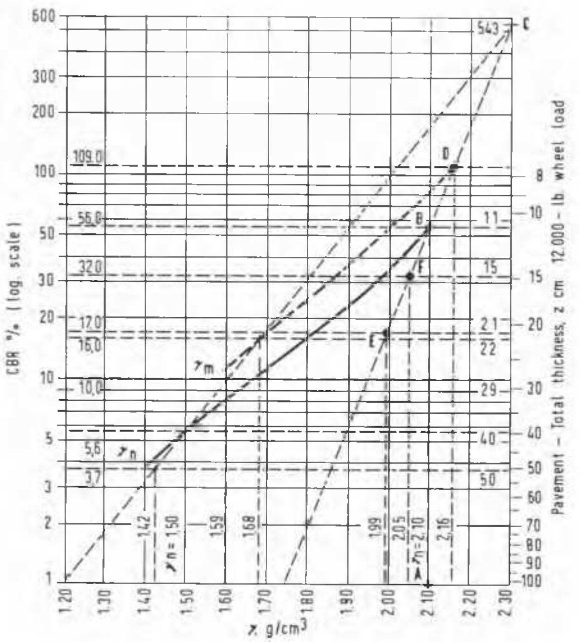

FIG. 6. γ, C.B.R., and Z values for two ideal medium soils.

The areas delimited in Fig. 4 are in accordance with the author's experience and also with the indications supplied by the literature (Roads Research Laboratory, 1961; Woods, *et al.*, 1960; and Yoder, 1959).

Examination of Fig. 6 shows that, as a mean: (1) the variation $\Delta\gamma$, in density, corresponds to variations in C.B.R., that is it increases as γ_n increases. (2) Considering relative variations ($\Delta\gamma/\gamma_n$), the influence of γ_n is even greater. (3) The pavement thickness (Z) is, however, inversely affected by variations $\Delta\gamma$, that is, for equal $\Delta\gamma$, the values of Z decrease as γ increases. (4) The value $\gamma'_m = 0.95\ \gamma_m$ is higher than γ_n when $\gamma_n < 1.90$ gram/cu cm and lower in the opposite case.

These conclusions show that: (1) The deficiencies of compaction are economically much more prejudical in the better soils (γ_n higher). (2) The change from the specification of the standard test to the modified one is economically more useful in poor soils (γ_n low), excluding the possible effect of expansion. (3) The specification for the density $\gamma' = 0.95\ \gamma_m$ will not bring advantage compared with specifying 100 per cent of γ_n.

After drawing the curves defined by the function $\overline{\text{C.B.R.}}_{np} = F_n\ (\gamma_n)$ in graphs of ordinates proportional to C.B.R. and of abscissas proportional to $1/(2.30 - \gamma_n)$ straight lines were approximately obtained. Thus:

$$\overline{\text{C.B.R.}}_{np} = K_1(1/2.3 - \gamma_n) - K$$
$$= K(\gamma_n - \gamma_\infty/2.3 - \gamma_n) \qquad (10)$$

where $\gamma_\infty = 2.3 - (K_1/K) = 1.1$ gram/cu cm and $\bar{K} = 11.3$. Also

$$\text{C.B.R.}_{n} = 11.3(\gamma_n - 1.1/2.3 - \gamma_n). \qquad (11)^*$$

The value $\bar{K} = 11.3$ is a mean value. In practice values of K between 5 and 23 were obtained for 95 per cent of the soils examined.

The value of $\gamma = \gamma_\infty$ corresponds to C.B.R. = 0, or zero bearing capacity. The soil will not bear its own weight, thus constituting a minimum below which it will not be possible to lower the density of a mineral soil of normal specific gravity ($G \geqslant 2.6$ gram/cu cm).

It has been found previously (Novais-Ferreira, 1962) that the maximum possible value of density of soils of $G \leqslant 2.73$ gram/cu cm is 2.30 gram/cu cm, and Eqs 9 and 10 confirm this.

Finally it can be concluded that common mineral soils ($2.60 \leqslant G \leqslant 2.73$ gram/cu cm) will show densities (γ) such that $1.1 \leqslant \gamma \leqslant 2.3$ gram/cu cm. The values obtained refer to means, the existence of one or two soils outside the limits mentioned being admissible. However, the exceptions will not be numerous, nor will the distance from the interval [1.1; 2.3] be considerable.

CONCLUSIONS

It can be concluded that:

1. A relation of the type log C.B.R. = $C_0 + C_1\ \gamma$, exists for each soil, C_0 and C_1 being constants dependent on that soil, providing the three conditions mentioned earlier (*supra*, 159) are observed.
2. The straight lines indicated show a common point ($\gamma = 2.3$ gram/cu cm; C.B.R. = 543 per cent) for the great majority of soils†.
3. The standard compaction test may give an approximate idea of the value of soil as embankment material (Fig. 6).
4. For soils of maximum density in the standard test greater than 1.90 gram/cu cm, it is preferable to specify, as minimum density in the field 100 per cent of the standard density instead of 95 per cent of the maximum density obtained in the modified test.
5. The variation range of the densities of the common mineral soils ($2.60 \leqslant G \leqslant 2.73$ gram/cu cm) should fall within the general interval $1.1 \leqslant \gamma \leqslant 2.3$ gram/cu cm; any exception will be rare and will not deviate greatly from the general interval indicated.

REFERENCES

A.S.T.M. Committee D–18 (1950). *Procedures for testing soils.* Philadelphia, American Society for Testing Materials.

A.S.T.M. Committee E–11 (1960). *A.S.T.M. manual on quality control of materials.* Philadelphia, American Society for Testing Materials (7th printing).

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*In the case of the A.A.S.H.O. modified compaction test, the constant would be $\gamma_\infty = 1.1$ and $K = 16$, but the adjustment is less correct and there was not a strong tendency to the value $\gamma_\infty = 1.1$, as in the case of the standard compaction test (Proctor).

†These two conclusions show considerable precision—constituting empirical laws of soils—since the conditions of the test performances are corrected with respect to moisture contents of compactions and soaking.

Campinos, F. P. (1959). *Ensaio de hipótese—distribuição lognormal dos CBR de campo.* Luanda, Laboratório de Engenharia de Angola (61).

Fisher, R. A., *et al.* (1954). *Tablas estadisticas para Investigadores Cientificos.* Madrid, Aguilar, SA. de Ediciones.

Klein, S. A. (1954). Possible developments in pavement foundation design. *Trans. South African Institution of Civil Engineers*, pp. 286–92.

Novais-Ferreira, H., e D. C. Crespo (1957). *Baridades e CBR dos solos nos terraplenos de estradas.* Luanda, Laboratório de Engenharia de Angola, (29).

Novais-Ferreira, H. (1962). *A variação de baridade nos solos.* Lisboa, Laboratório Nacional de Engenharia Civil, 173 pp.

——— (1963). *Compaction curves.* Luanda, Laboratörio de Engenharia de Angola (95).

Road Research Laboratory (1957). *Soil mechanics for road engineers*, pp. 66–7 and 81. London, Her Majesty's Stationery Office.

Woods, K. B., *et al.* (1960). *Highway engineering handbook*, chap. 25, p. 15; chap. 15, p. 16. New York, McGraw-Hill Book Company.

Yoder, E. J. (1959). *Principles of pavement design,* p. 185. New York, Wiley & Sons.