

A RAPID ASSESSMENT OF SOIL STRENGTH PROPERTIES

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ABSTRACT

Mathematical relationships between soil strength parameters are established. From only a few laboratory tests, performed within a twenty four hour period, the assessment of a soil's achievable condition and possible use prior to placement is enabled. From the DCP test with a moisture content reading the relative compaction, soaked CBR and density of a compacted layer can be assessed. In an appendix the derivation of mathematical relationships, together with a comprehensive table of these relationships is given.

1 A CALL FOR RAPID EVALUATION

There is a clause in road contract specifications which clearly places the onus on the contractor to ensure that all materials forming part of the road structure shall conform to specified requirements. To this end it behoves the contractor to perform soil tests on the materials proposed for use. The contractor would also like to know, as soon as possible, if any soil he proposes to use will yield, under normal compactive effort, an achievable density and strength at least equal to that specified.

In order to determine the strength potential of a soil for suitability in a road foundation layer a fair number of soil laboratory procedures are normally performed, but it may be up to seven days or more after submission before results come to hand.

The use of mathematical relationships relating soil properties requires only a few laboratory tests which can all be completed in less than twenty-four hours, and the use of the modern PC enables the solution of these relationships to be obtained within minutes.

Note 1: It is not intended that the methods of soil strength assessment described here should replace conventional testing methods for final approval of work but they could be useful in the rapid assessing of a soil's possible use and the condition of compacted layers prior to submission for approval.

Note 2: An inspection of actual field results in order to substantiate the validity of the mathematical approach suggested in this paper, the writer found that as a result of the absence of bulk relative density figures of the soil particles he was unable to make any meaningful comparisons. It is indeed a pity that testing for relative density, the bulk of soil particles is not included as an essential routine when all materials are analysed instead of only crushed rock.

2 TERMS AND SYMBOLS DEFINED

The strength of a soil is dictated by two important conditions, namely: a) the ratio of the voids to that of the solids; termed the Voids Ratio, E and b) the volume of the water in the voids to that of the solids; termed the Water Ratio, R . The Bulk Relative Density, G_{bk} , of the soil particles must be known in order to determine values for E and R . The symbol E is used here for the voids ratio in lieu of the conventional e as it is deemed to be defined by G_{bk} and not G_{app} . If D and W represent a soil density and moisture content respectively then:

$$E = (G_{bk}/D) - 1 \text{ and } R = W G_{bk} \quad (1)$$

Terms which are commonly used to indicate soil strength are inter alia:

Soil Density, D: This defines the mass per unit volume of a compacted soil. A field density, D_f is not a direct indication of strength since the relative density of the particles as well as compaction effects its value. Only when D_f is related to a laboratory maximum density, D_m , as a degree of relative compaction is its strength indicated, since D_m is related to a CBR value. The symbol D is used here in place of the conventional γ to coincide with the D in the term MDD for maximum dry density.

Soil Group, Gg: It classifies soil between a G4 for a good gravel and a G10 for a very weak soil. As a mathematical symbol the letter g in the Gg term, represents a whole number indicating the soil's group and a decimal, which gives the soil's strength position within the group. (G1 to G3 refer to crushed stone, not dealt with here).

Particle relative density, Gapp and Gbk: Due to the weathering process of breakdown, soil particles have surface cracks which are actually air voids in the body of the particles. The volume of the particles of mass M , may be either excluding these voids (apparent volume, V_a) or including the voids (bulk volume, V_b). $G_{app} = M/V_a$ and $G_{bk} = M/V_b$ The factual volume of the solids in a soil mass includes the crack voids and is the bulk volume.

Solids Ratio, L: This represents the state of togetherness of solids in a soil mass. It is the ratio of the bulk volume of the solids to that of the total volume of solids and interparticle voids, or in other words, the ratio of the mass density of the solids to their bulk relative density.

It is a more direct measure of strength than density; being a ratio, independent of mass and is calculated by:

$$L = D/G_{bk} \quad (2)$$

Then term solids used in this paper is deemed to mean bulk volume solids, which include the crack volume V_c .

Void Ratio, E: The volume of the voids relative to the volume of the solids. This property is a direct measure of a soil's strength at a water ratio of R . The minimum value of the voids ratio, E_m , is reached when the Degree of Saturation is 80%. A mathematical relationship between E and R under a fixed compactive effort, the MDD curve, was developed by Savage (2012) (See Appendix). The voids ratio is related to the solids ratio L and density D , as follows:

$$E + 1 = 1/L = G_{bk}/D \quad (3)$$

The degree of Saturation, S: The ratio of the volume of the water in the soil to the volume of the free or interparticle voids and is given by $S = R/E$. Note that when $S = 0,8$, R is equal to $0,8E$ and is equivalent to the OMC in W terms.

Relative Compaction, RC: Relates the field density to a maximum density obtained by a laboratory testing procedure and which has been given a strength test referred to as the soaked CBR, i.e. B_{ms} at maximum density. Relative compaction is equated to the solids ratio L , and the voids ratio E , as follows:

$$RC = D_f/D_m = L_f/L_m = (E_m + 1)/(E_f + 1) \quad (4)$$

Compression Strength Index, C: As defined by Savage (2012) the dry leg of the moisture/density curve is a strength contour and represents the soil's resistance C , to, or strength against, further densification at the degree of moisture present, due to the compactive effort applied. This resistance to further compression termed the compression strength, C , is governed by the voids ratio, E , and the moisture or water ratio, R . It should be noted that factors such as grading, particle shape and roughness and clay regulate the densification of the soil under a given effort and automatically adjusts the value of C .

Dislocation Factor, F: The ratio of the California Bearing Ratio, B , and the compression strength, C of a compacted soil, where $F = B/C$. The strength C is a constructive resistive strength, (active) while the strength B , (CBR) is a destructive or dislocation resistive strength (passive) and is generally the larger of the two strengths. A barbed arrow may readily enter a target but may be more difficult to extract. This may be likened to the active

and passive pressure theory of Terzaghi (1948). It should be noted that the true parameters relating to the strength of compacted soil relate Volume conditions or ratios and are independent of the soil mass or density.

3 SOIL STRENGTH PROPERTIES MATHEMATICALLY RELATED

The detailed derivation of mathematical relationships between soil parameters is recorded in the appendix hereto. The suffix, a, appended to the terms relative compaction, RCa, solids ratio, La, and compression strength, Ca, indicates the possible maximum condition of densification, achievable under normal field compactive effort of say six to eight roller passes.

Experience has shown that a G4, gravel can readily be compacted to an RCa of 98% and that a high quality G4 gravel may reach a corresponding RCa of 99%. Likewise a very poor G10 soil may show a lower limit of only 89% for RCa. With the limits of 4,0 and 10,0 for Gg and corresponding limits of 0,99 and 0,89 for RCa, these two parameters can be related in the general exponential form:

$$RCa = m Gg^n = 1,163Gg^{-0,116} \quad (5)$$

In the appendix limit values for La, Ca and Ea are established. From this data their exponential relationships have been formulated. As $Lm = La/RCa$ the corresponding limits for Lm, Em and Cm were also established and their relationships formulated. Figure 1 is a flow diagram showing the steps taken in the establishment of corresponding property limits

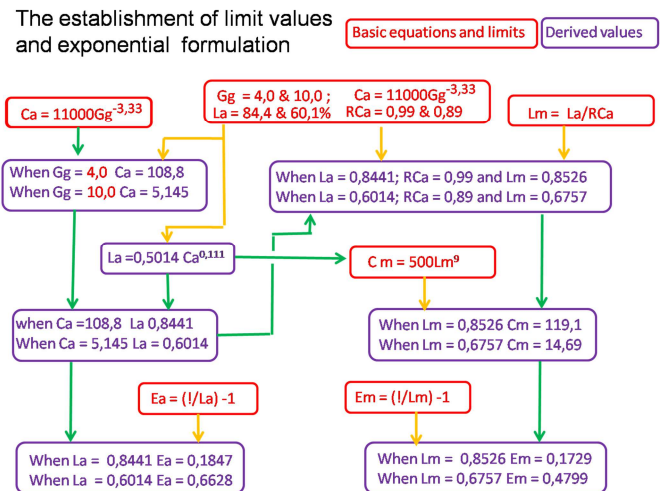


Fig.1. Flow diagram of steps followed in the establishment

4 SOIL SUITABILITY ASSESSMENT PRIOR TO APPLICATION

The compaction requirements for each layer in which a soil is to be placed must be reasonable for the material and should preferably not require a specified strength which exceeds the achievable density strength of the soil. In other words, the required relative compaction should preferably not be greater than the achievable relative compaction, i.e. RCf should not exceed RCa. For example: the normal minimum requirements for RCf for a base course. Subbase and selected layer are 98; 95; and 93% respectively. To enable the contractor to assess if this is acceptably possible for the soil he proposes to use, he may be required to undertake the following soil laboratory operations:

- Drying out the soil by sun or oven for the preparation of soil specimens
- A modified density test (MDD) in order to obtain maximum dry density
- Soaked CBR tests at different densities to estimate soaked CBR at RCf
- Moisture content determination by oven drying

The execution of these tests, performed in sequence, is time consuming and seven to ten days may lapse before results are reported, which time may be extended if a large number of soil samples is to be tested.

A relatively rapid shortcut involving only a few laboratory tests, easily completed within 24 hours and some calculations, can enable a quick assessment to be made of a soil's possible achievable strength.

If the relative density of the soil particles, G_{bk} is known the maximum density voids ratio E_m can be calculated even if only one moisture density operation giving a voids ratio E , and water ratio R , is performed. Savage (2012) established an equation which defines the MDD curve in terms of E and R (See Appendix below). The only laboratory tests required are thus:

A single moulded compaction of soil at natural or low moisture content, to obtain a test density D_t at a moisture content W Immediate determination of unsoaked CBR on the moulded material, to get an in-situ CBR, B_i , at the density, D_t . Bulk relative density of the soil particles, G_{bk} .

When values for D_t , W , B_i and G_{bk} for a given soil are known, proceeding along the flow pattern as given in Figure 2 enables the following properties of the soil to be assessed:

- the achievable voids ratio E_a
- the achievable relative compaction RC_a
- the achievable compression strength C_a
- the soaked CBR at maximum density B_{ms}
- the soaked CBR at achievable density B_{as}
- the soil group and position within the group G_g

A specification may require that both a minimum relative compaction as well as a minimum CBR must be met. The calculation of a value for RC_a and B_{as} as shown above will enable the contractor to assess if a particular material will meet specified requirements or not under normal compactive effort.

4.1 Numerical example

Given from laboratory tests:

Single moisture–density test: $D_t = 2,0427 \text{ t/m}^3$ and $W = 4,2\%$

Un-soaked CBR on this moulded soil at density D_t : $B_i = 127,1$

Relative density of soil particles: $G_{bk} = 2,72$

Will this soil be suitable for use in a sub-base layer where minimum $B_{fs} = 45$ and minimum $RC_f = 95\%$?

From the flow diagram above: (Only limited rounding off has been applied to avoid accumulated error)

$$E = (G_{bk}/D_t) - 1 = (2,72/2,0427) - 1 = 0,3322$$

$$R = WG_{bk} = 0,042 \times 2,72 = 0,1142$$

$$S = R/E = 0,1142/0,3322 = 0,3438$$

$$E_{o+1} = 0,5(E + 0,5556R) + 1 = 0,5 \times 0,3322 + 0,2778 \times 0,1142 + 1 = 1,1978$$

$$C_i = 500(E_{o+1})^{-9} = 500(1,1978)^{-9} = 98,49$$

$$F = B_i/C_i = 127,1/98,49 = 1,291 = 1,29 \text{ say}$$

$$E_m = E(0,59S + 0,57) = 0,3322(0,59 \times 0,3438 + 0,57) = 0,2567$$

$$C_m = 500(E_m + 1)^{-9} = 500(1,2567)^{-9} = 63,96$$

$$B_{ms} = F \times C_m = 1,29 \times 63,96 = \underline{82,50}$$

$$E_{fa} = 0,9389(E_m + 1)^{1,4582} - 1 = 0,9389(1,2567)^{1,4582} - 1 = 0,3101$$

$$RC_a = 1,044(E_{fa} + 1)^{-0,314} = 1,044(1,3101)^{-0,314} = \underline{95,91\%}$$

$$C_a = 500(E_{fa} + 1)^{-9} = 500(1,3101)^{-9} = 43,98$$

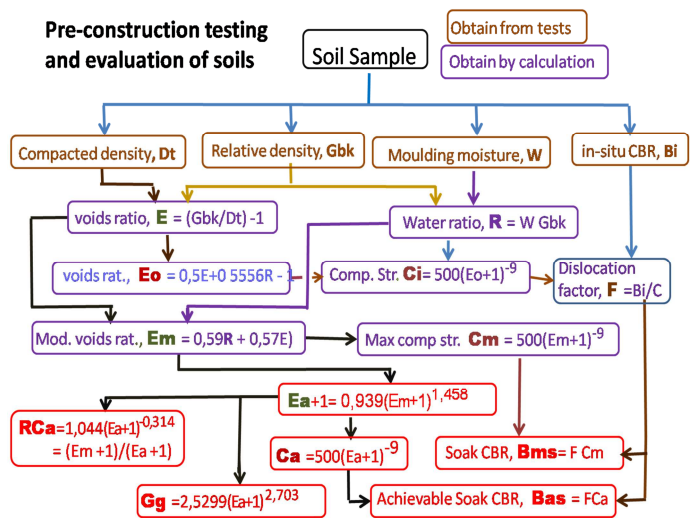


Fig. 2 Flow diagram for the early assessment of soil properties

$$Bas = Ca \times F = 43,98 \times 1,29 = \underline{56,73}$$

$$Gg = 2,5299(Efa + 1)^{2,7028} = 2,5299(1,3101)^{2,7028} = \underline{5,25}$$

Note that the value for Em has been determined by means of the simplified formula:

$$Em = E(0,59S + 0,57) = 0,57E + 0,59R \quad (6)$$

to give a value of 0,2567 for Em. Applying the same values for E and R in the extended formula for Em, the value is 0,2560 (See equation A2, in Appendix).

The soil group is a safe G5 for subbase. The achievable soaked field Bas is 56,7 well above the specified requirement of 45 but the achievable relative compaction of 95,90% is a bit borderline. Here the strength of the layer is satisfactory and if used in the layer it will be strong enough but when placed, the achieved relative compaction may drop below specification requirements in some areas. Some extra rolling is advised to overcome this risk. If a risk free RC margin of say 96,5 is set, based on work done by Forssblad (1981) the writer suggests the following as a means of estimating the extra effort required to meet this safe relative compaction requirement:

$$\text{Effort to meet spec} = (RC_{\text{safe}} / RC_a)^{13} \quad (7)$$

The calculation process as detailed above can be readily programmed in a computer which will give all the answers in a matter of seconds. Although not determined in the above exercise, values for the maximum solids ratio, Lm and achievable Lfa can readily be calculated; thus:

$$Lm = 0,5014Cm^{0,111} = 0,5014(63)^{0,111} = 79,54\%$$

$$\text{And } Lfa = 0,5014Ca^{0,111} = 0,5014(43,02)^{0,111} = 76,15\%$$

From the data presented in table A2 in the Appendix the chart in Figure 3 was prepared and can also be used to assess achievable property values when Em has been evaluated from:

$$Em = (Gbk/D_{\text{mod}}) - 1 \text{ or } Em = 0,57E + 0,59R \quad (8)$$

The values in the above example are confirmed by the red line cursor through Em = 25,7%

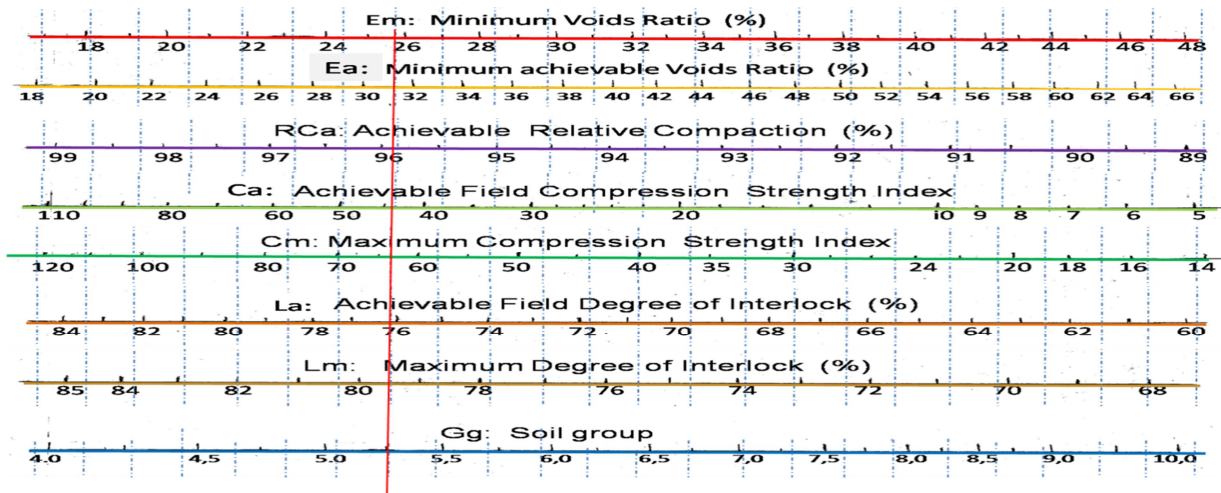


Fig. 3 Alignment chart for rapid assessment of achievable soil properties

If only RCa and Bas are required the above series of equations can be condensed to the following if E and R are obtained from Dt and W and the factor F is also known:

$$RCa = 1,377(E + 1,035R + 1.754)^{-0,458} \quad (9)$$

$$Bms = Bi\{(Eo+1)/(Em+1)\}^9 = 500F(0,57E + 0,59R + 1)^{-9} \quad (10)$$

$$Bas = Bi\{(Eo+1)/(Ea+1)\}^9 = 500F(0,546E+0,565R+0,958)^{-0,13,12} = BmsRCa^{0,1111} \quad (11)$$

5 POST CONSTRUCTION ASSESSMENT

When a layer has been compacted an assessment of its relative compaction, RCf, its field soaked CBR, Bfs and other strength parameters can be made by a DCP test coupled with a moisture content determination. The procedure followed is best described by an example:

It is assumed that the material was tested for approval prior to placement and that the bulk relative density of the soil particles is known and that the dislocation factor F is also known.

Let these values be as for the above example where Gbk = 2,72 and F = 1,29. Assume further that a DCP test gave a DN value of 2,95 mm/blow, with a moisture content of 2,9%. Figure 4 shows a flow diagram of the steps taken in the assessment of the in-situ CBR, Bi, the soaked field CBR, Bfs, relative compaction RCf, and the cone field density Dfc. The figures below each step are the values obtained at each step. The equation

$$Bi = 500(DN + 0,5)^{-1,3} \quad (12)$$

relating the in-situ CBR, Bi, and DN was derived from a tabular relationship prepared by Kleyn (1984) and which the writer has formulated into mathematical terms.

As the RCf is only 93,6%, which is below the achievable value of almost 96%, as determined in the above pre-construction study, (See Figure 3), the contractor evidently had not applied the full normal compactive effort prior to testing.

It should be noted that the cone voids ratio Ec determined from the CBR instead of the compression strength C is less than the true voids ratio, E where:

$$E + 1 = F^{0,1111}(Ec + 1) \quad (13)$$

The value of RCf is the same as RCfc as the ratio cancels the $F^{0,1111}$ term but the true field density, Df will be lower than the cone density: Dfc i.e:

$$Df = Dfc / F^{0,1111} \quad (14)$$

If values for true Em, Ef, Dm, and Df are required these can be obtained by following the flow as given in Figure 5. If only the in-situ

CBR, Bi and the field soak CBR, Bfs and relative compaction RC are required these values may be obtained directly from:

$$Bi = 500 (DN + 0,5)^{-1,3} \quad (15)$$

$$Bfs = (2 Bi^{-0,1111} - 0,557R - 0,501)^{-9} \quad (16)$$

$$RC = (Bi^{-0,1111} - 0,0i9R - 0,0616) / (1,754Bi^{-0,1111} - 0,4887R - 0,4398) \quad (17)$$

Equations 16 and 17 are derived from the relationships shown in Figure 4 and established in Table A1 in the appendix hereto.

Note. An error of 2% in the determination of DN and the moisture content can result in an accumulative error of 0,4% and 6,7% in RC and Bs respectively. Accurate field and laboratory testing is thus indicated.

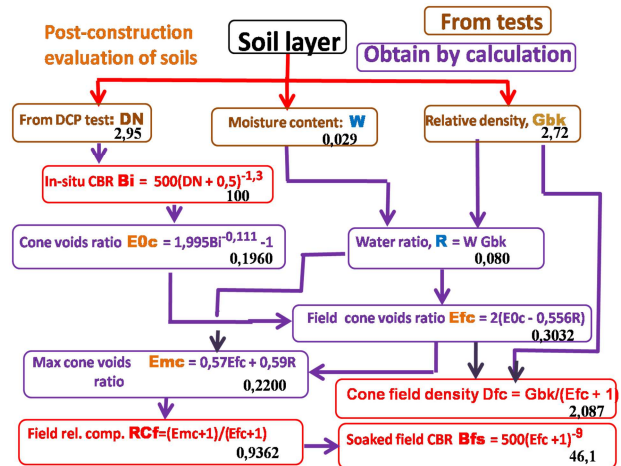


Fig.4. Flow diagram for the assessment of post construction conditions

The figures below each step are the values obtained at each step. The equation

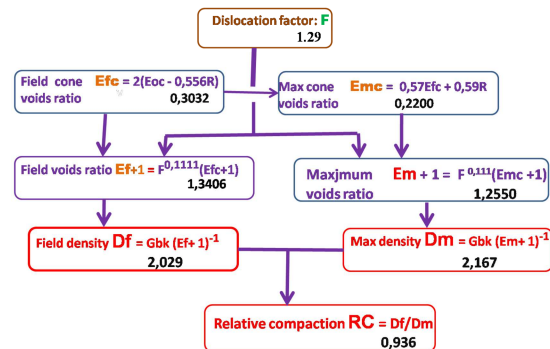


Fig. 5 Flow diagram to assess values for Dm, D and RC

6 EVALUATION BY GRAPHICAL MEANS

If a high degree of accuracy is not required a shortcut procedure free of calculations may be followed by the use of the graph given in Figure 6. Entering the chart at the DN value of 2,95 and at the water ratio of 8% and then following the directions as indicated by the various arrows the CBR and cone voids ratio values as calculated above may be read in a rounded off form. Note that the light green arrow indicating a value for E_{mc} springs from the degree of saturation line, $S = 80\%$ for maximum density for the field soil.

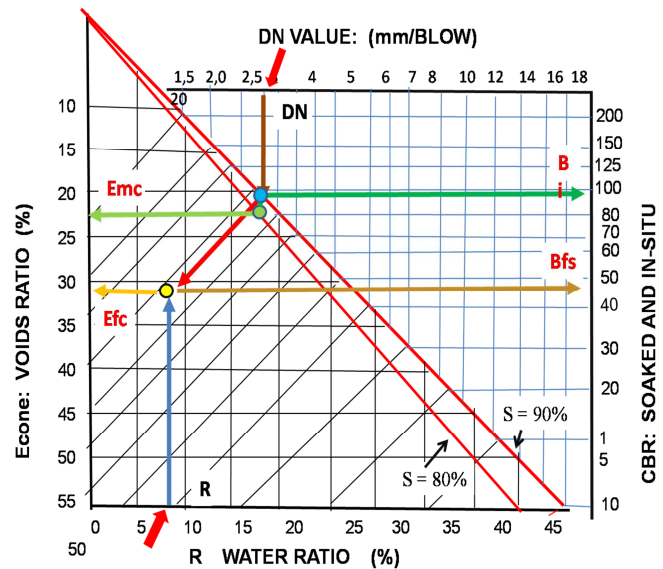


Fig. 6 The rapid assessment of CBR and cone voids ratios by graphic plotting

7 CONCLUSION

A soil's strength properties can be rapidly assessed prior to the actual placing of the soil by the performance of only a few laboratory tests which can all be completed in less than 24 hours, followed by mathematical calculations. These few tests are:

The bulk relative density of the soil particles to get G_{bk} .

One compaction test to get D_t and W .

An in-situ CBR test (un-soaked) on this compacted soil to get B_i .

This exercise done on a proposed soil can provide inter alia the following:

Achievable relative compaction, RC_a

Soaked CBR at maximum density and at achievable density, B_{ms} and B_{as}

Maximum and achievable voids ratio, E_m and E_a

Soil group and position within the group G_g

By performing a DCP test on a compacted soil layer together with a moisture content determination the following properties can be determined:

The in-situ CBR, B_i

The field soaked CBR, B_{fs}

Relative compaction, RC

Field density D_f

It is recommended that the test for bulk relative density G_{bk} be incorporated as an indicator test for all soils in future.

APPENDIX

A1 MAXIMUM VOIDS RATIO E_m FROM E AND R

A single laboratory compaction test preferably at natural moisture content is all that is necessary to assess the soil's maximum density, provided that the particle bulk relative density, G_{bk} is known.

Let this density be D_t at a relatively low moulding moisture W . The voids ratio E at this density is given by $E = (G_{bk}/D_t) - 1$, and the water ratio R is given by $R = WG_{bk}$

The MDD curve in terms of E and R and the maximum voids ratio, E_m , has been mathematically formulated by Savage (2012):

$$(9E - 8E_m)^2 - (10R - 8E_m)^2 - E_m^2 = 0 \quad (A1)$$

$$\text{or } E_m = \{(72E - 80R)^2 + (81E^2 - 100R^2)\}^{0.5} - (72E - 80R) \quad (A2)$$

As equations A1 and A2 are cumbersome the writer developed an improved approximation for E_m . The equation can now be expressed in terms of the degree of saturation and the ratio of E_m to E :

$$E_m = E(0,59S + 0,57) \quad (A3)$$

Provided S falls between 20 and 60% this gives a value for E_m with a maximum error of less than 0,5%.

Equation (A3) is an improvement of the previously simplified equation:

$$E_m = 0,56E + 0,63R \quad (A4)$$

A2 ESTABLISHING LIMIT VALUES AND RELATIONSHIPS

The writer's experience, in relating soil properties mathematically, has shown that, apart from relationships which relate certain properties physically, exponential functions can be said to govern the relationships within the limits of the engineer's interest with reasonable accuracy. The general equation is in the form of:

$$Y = mX^n \quad \text{or} \quad \lg Y = n \lg X + \lg m \quad (A5)$$

In order to determine values for m and n , corresponding limit values for Y , (y_1 and y_2) and X , (x_1 and x_2) were fixed so that:

$$n = (\lg y_1 - \lg y_2) / (\lg x_1 - \lg x_2) \quad \text{and} \quad m = y/x^n \quad (A6)$$

Based on experience gained in soil behaviour, the writer considers the following as acceptable:

For a G4 soil an achievable RCa of 99% of modified density is possible under normal compactive effort and for a G10 soil the RCa is 89%

Savage (2012) has shown that for a good G4 gravel, say G4; an achievable solids ratio L_a , of 0,85 can be achieved. ($L_a = 88\%$ is readily achieved for a G1 material)

On the other end of the Soil group scale the achievable value for L_a is in the order of 60%.

Minimum field CBR values, B_{fs} , for the different soil groups as set by COLTO

(2006) can be equated to a straight line on a log/log plot with reasonable accuracy,

(Figure A1) and may be represented by:

$$B_{fs} = 15000Gg^{-3,33} \quad (A7)$$

From this, if the value of the compression strength index C_a , is arbitrarily set as 75% of the minimum CBR, the equation becomes:

$$C_a = 11000Gg^{-3,33} \quad (A8)$$

Applying equation (A8) when $Gg = 0,99$ and $0,89$ the C_a limits are 108,8 and 5,145.

As the relationship between C and Gg is exponential it is reasonable to assume that L and Gg are also related exponentially and using limits for L_a of 0,85 and 0,60, the following was formulated:

$$L_a = 1,41Gg^{-0,366} \quad (A9)$$

Combining these two equations (A8) and (A9) gives the general relationship between C and L as:

$$C = 481L^{9,1075} \quad \text{or rounding off} \quad C = 500L^9 \quad (A10)$$

Using the limits of 108,8 and 5,145 for C_a and applying equation (A10) the limits for L_a can now be found to be 0,8441 and 0,6014. The Degree of interlock at modified density, L_m is related to L_a by $L_m = L_a/RCa$ and the limits for L_m are thus 0,8525 and 0,6742.

Similarly, by using equation (A10) and L_m limits, the limits for the compression strength

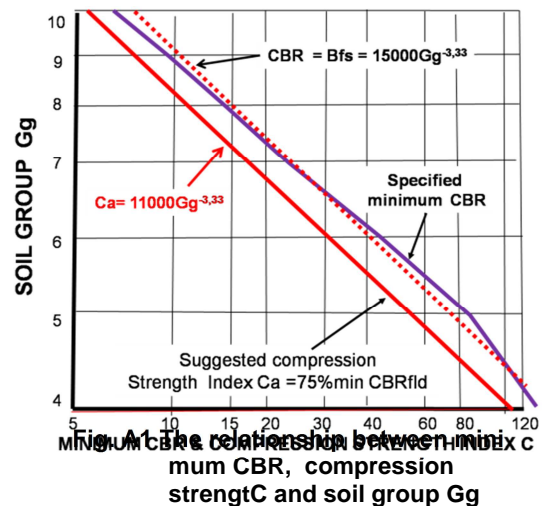


Figure A1 CBR relationship between minimum CBR, compression strength C and soil group Gg

Cm at modified density are fixed at 119,1 and 14,69. (In order to reduce accumulated errors, results to four significant figures have generally been adopted.)

Combining equation (A10) and $L = 1/(E + 1)$ we get:

$$C = 500\{1/(E + 1)\}^9 \quad (A11)$$

From equation (A11) and the limits set for Ca and Cm, the limit values for Ea and Em can also be determined. Table A1 lists the fixed limits for the various strength parameters which enabled the establishment of exponential functions relating them. From this table of corresponding limit values for the soil properties Table A 2 was prepared

TABLE A1 Limit values for strength parameters

Soil Property:	G	RCa	Lm	La	Cm	Ca	Em	Ea
Maximum:	10,0	0,99	0,8526	0,8441	119,1	108,8	0,1729	0,1847
Minimum:	4,0	0,89	0,6757	0,6014	14,69	5,145	0,4799	0,6628

TABLE A2. Mathematical relationships between soil strength parameters

	La	Cm	Ca	RCa	Gg	Ea + 1	Em + 1
Lm	La = 1,065Lm ^{1,458} Lm = 0,958La ^{0,686}	Cm = 500Lm ⁹ Lm = 0,5014Cm ^{0,111}	Ca = 881,9Lm ^{13,12} Lm = 0,5964Ca ^{0,076}	RCa = 1,065Lm ^{0,458} Lm = 0,872RCa ^{2,184}	Gg = 2,134Lm ^{-3,940} Lm = 1,212Gg ^{-0,254}	Ea+1 = 0,939Lm ^{-1,458} Lm = 0,9577(Ea+1) ^{-0,686}	Em+1 = Lm ⁻¹ Lm = (Em+1) ⁻¹
Lm	La	Cm = 339,1La ^{6,173} La = 0,389Cm ^{0,162}	Ca = 500La ⁹ La = 0,501Ca ^{0,111}	RCa = 1,044La ^{0,314} La = 0,872RCa ^{3,183}	Gg = 2,53La ^{-2,703} La = 1,41Gg ^{-0,370}	Ea+1 = La ⁻¹ La = (Ea + 1) ⁻¹ - 1	Em+1 = 1,044La ^{-0,686} La = 1,065 (Em+1) ^{1,485}
		Cm	Ca = 0,102Cm ^{1,458} Cm = 4,777Ca ^{0,686}	RCa = 0,776Cm ^{0,051} Cm = 145,1RCa ^{19,65}	Gg = 32,43Cm ^{-0,438} Cm = 2825Gg ^{-2,284}	Ea+1 = 2,569Cm ^{-0,162} Cm = 339,1(Ea+1) ^{6,173}	Em+1 = 1,991Cm ^{-0,111} Cm = 500(Em+1) ⁻⁹
			Ca	RCa = 0,841Ca ^{0,035} Ca = 145,1RCa ^{28,66}	Gg = 16,35Ca ^{-0,300} Ca = 11,00Gg ^{-3,330}	Ea+1 = 1,995Ca ^{-0,111} Ca = 500(Ea+1) ⁻⁹	Em+1 = 1,677Ca ^{-0,076} Ca = 882,4 (Em+1) ^{-13,12}
				RCa	Gg = 3,669RCa ^{-8,605} RCa = 1,163Gg ^{-0,116}	Ea+1 = 1,147RCa ^{-3,184} RCa = 1,044 (Ea+1) ^{-0,314}	Em+1 = 1,147RCa ^{-2,183} RCa = 1,065 (Em+1) ^{-0,458}
					Gg	Ea+1 = 0,709Gg ^{0,370} Gg = 2,530(Ea+1) ^{2,703}	Em+1 = 0,254 Gg = 2,134(Em+1) ^{3,941}
						Ea+1	Ea+1 = 0,939(Em+1) ^{1,458} Em + 1 = 1,044 (Ea + 1) ^{0,686}

A3 ESTABLISHING THE EQUATIONS FOR Bfs AND RC

A value for Bi is obtained from equation 15: $Bi = 500(DN + 0,5)^{-1,3}$. The relationship between voids ratio E and a strength parameter C is given in Table A2. As $E + 1 = 1,995C^{0,111}$ which in terms of CBR becomes:

$$Eoc + 1 = 1,995Bi^{-0,1111}, \quad (A12)$$

Now, as established by Savage (2012):

$$Efc = 2Eoc + R/0,9 \quad (A13)$$

Combining equations (A12) and (A13):

$$Efc + 1 = 3,989Bi^{-0,1111} + 1,1111R - 1 \quad (A14)$$

From $Emc = 0,57Efc + 0,59R$ (Equation 8) and (A14):

$$Emc + 1 = 2,2738Bi^{-0,1111} - 0,043R - 0,14 \quad (A15)$$

Now $RC = (Emc + 1)/(Efc + 1)$ and dividing (A14) and (A15) by 2,2738 we get:

$$RC = \frac{Bi^{-0,1111} - 0,019R - 0,0616}{1,7544Bi^{-0,1111} - 0,4887R - 0,4398} \quad (A16)$$

Rearranging (A12) and substituting:

$$Bfs = (2 Bi^{-0,1111} - 0,557R - 0,501)^{-9} \quad (A17)$$

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SYMBOLS

C	Compressive strength index; resistance to further densification under applied effort
Ca	Compressive strength index at achievable density
Cf	Compressive strength index at field density
Cm	Compressive strength index at maximum density
B	California Bearing Ratio
Bas	Soaked California Bearing Ratio at achievable density
Bfi	In-situ California Bearing Ratio at actual field density
Bfs	Soaked California Bearing Ratio at actual field density
Bi	In-situ California Bearing Ratio at moulded or field density and moisture content
Bms	Soaked California Bearing Ratio at maximum density
D	Density of compacted soil
Df	Field density of compacted soil (t/m^3)
DN	Dynamic cone penetration rate (mm/blow)
Dt	Density by means of a laboratory test
E	Voids ratio: ratio of free voids volume to bulk solids volume
Ea	Achievable voids ratio
Ef	Field voids ratio
Em	Voids ratio at maximum density
Eo	Hypothetical voids ratio with soaked strength equal to in-situ un-soaked strength
F	Dislocation factor: ratio of CBR to Compression strength
Gg	Soil group
Gapp	Apparent relative density of soil particles; volume of cracks excluded as solids vol.
Gbk	Bulk relative density of soil particles; volume of cracks included as solids volume
L	Solids ratio; ratio of bulk solids volume to total volume
Lm	Solids ratio at maximum density
R	Water ratio: ratio of water volume to bulk solids volume
RC	Relative compaction: ratio of field density to maximum density
RCa	Achievable Relative compaction
RCs	Specified minimum relative compaction at required field density
W	Water content within a compacted soil