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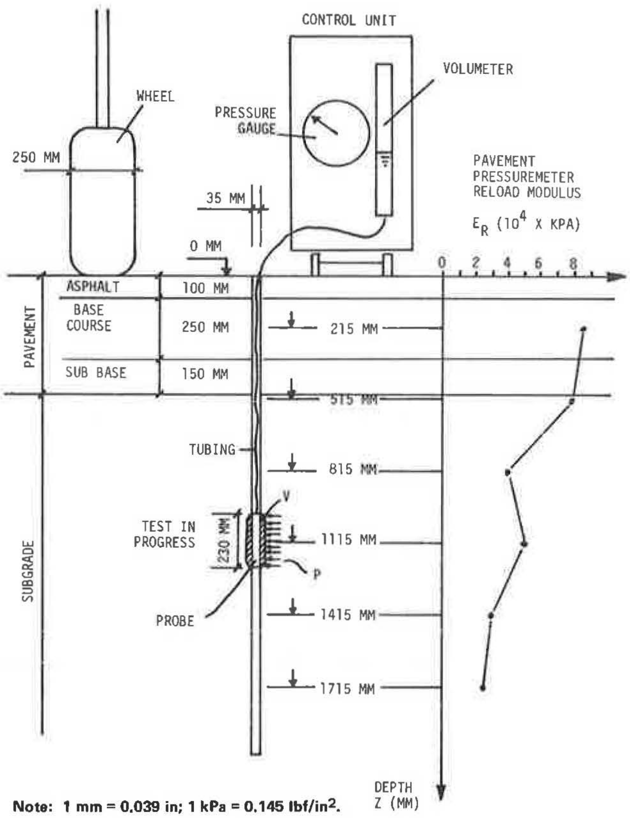
Use of Pressuremeter Test to Predict Modulus and Strength of Pavement Layers

JEAN-LOUIS BRIAUD AND DONALD H. SHIELDS

Most airport pavements are designed or evaluated on the basis of a plate test. This article shows how a pressuremeter test can replace plate tests to advantage. A 1-in diameter hole is made through the pavement and pressuremeter tests are run every foot down to a depth of 6 ft. Each test yields a deformation modulus, so that a modulus profile is obtained at each hole location. The results of a comparison between 93 pavement pressuremeter tests and 11 plate tests performed at two airport sites indicate that the pavement pressuremeter can be used for pavement design; the plate tests performed were standard for the design of airport pavements in Canada. A chart for the design of flexible airport pavements by using the results of pavement pressuremeter tests is presented. A procedure based on multilayer elastic theory is also discussed. This procedure uses the pressuremeter modulus as the elastic modulus of each layer. The multilayer elastic procedure makes more thorough use of the pressuremeter test results than does the chart procedure.

Most airport pavements are designed or evaluated on the basis of a plate test. This article shows how a

Figure 1. Pavement pressuremeter test.



Note: 1 mm = 0.039 in; 1 kPa = 0.145 lbf/in^2.

pressuremeter test can replace advantageously plate-bearing tests and how a pavement can be designed or evaluated on the basis of pressuremeter tests results.

A pressuremeter test (1) (Figure 1) consists of placing a cylindrical expandable probe in a borehole and then inflating the probe. A control unit on the ground surface generates the pressure necessary to inflate the probe. The pressure against the wall of the borehole (p) and the expansion of the cavity (v) are recorded, and a p-v curve is plotted (Figure 2). A modulus of deformation is obtained from the slope of the curve (A to B on Figure 2) and, in the standard test used for foundation design, a limit pressure is read at large strains (E on Figure 2). In the case of pavement design and evaluation, only the modulus of deformation is of interest, and the test can be terminated as soon as point B is reached. This simplifies considerably the design of the pressuremeter.

Pressuremeters for foundation engineering are available commercially, but the commercial models are unsuitable for the tests described here. Both the recommended apparatus and the test procedure have been described in detail elsewhere (2,3).

For pavement engineering, pressuremeter tests have to be performed at very shallow depth, and some concern was expressed initially that a lack of confining pressure at shallow depth would lead to deformation moduli values that were too low. It was shown (2) that, even very close to the ground surface, the pressuremeter-derived deformation modulus is consistent with the pressuremeter-derived deformation modulus measured at larger depth.

Two ways in which deformation information can be used to design new pavements (subbase, base, and surface course) or to evaluate existing pavements are as follows:

1. An empirical approach in which a correlation is found among deformation moduli, design, and performance, and
2. A theoretical approach where moduli are entered into a mathematical model of a pavement.

Both approaches were used in the work covered by this article. For the empirical approach, use was made of existing design charts based on plate-bearing tests by converting pressuremeter data, in effect, to an equivalent plate-bearing test result; the conversion procedure was obtained from the results of comparison tests between the standard plate test, which is used for airport pavement design in Canada, and pressuremeter tests. Multilayer elastic theoretical representation of a pavement appears ideally suited to the theoretical approach to design by using pressuremeter data. This theoretical approach offers an advantage over the empirical approach in that each pressuremeter test result can be used directly.

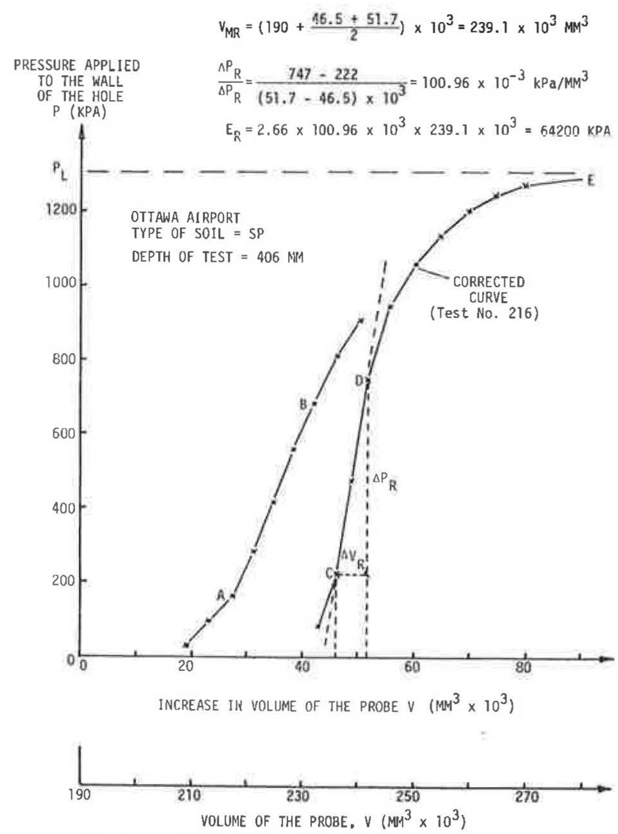
PAVEMENT PRESSUREMETER TEST

The pavement pressuremeter (Figure 3) (2,3) consists of a probe, tubing, and a control unit. The probe is a cylinder 32.5 mm (1.33 in) in diameter that is inflatable to a diameter of 39.5 mm (1.61 in). The inflatable part of the probe is 230 mm (9.1 in) long. The tubing is made of nylon, 6 mm (0.24 in) in outside diameter, and 2 mm (0.08 in) in inside diameter. It is about 5 m (16.4 ft) long.

The control unit (Figure 3) is housed in a plywood box 1.2 m (47.2 in) long, 0.6 m (23.6 in) wide, and 0.3 m (11.8 in) deep. The control unit serves three purposes:

1. It generates the pressure necessary to inflate the probe,

Figure 2. Typical pavement pressuremeter curve.



Note: 1 mm = 0.039 in; 1 kPa = 0.145 lbf/in^2.

Figure 3. Components of pavement pressuremeter.

2. It indicates on a pressure gauge what this pressure is at any time, and
3. It indicates on a volumeter what volume of liquid has been sent to the probe.

A hand pump is used to generate the pressure. By rotating the wheel of the hand pump, a piston advances and forces water through the volumeter. This water displaces a column of red kerosene in two parallel plexiglass tubes. The kerosene-water interface facilitates the reading, on a scale, of the volume of water sent to the probe. The control unit was designed specifically for the execution of strain-controlled tests and for imposing unloading-reloading cycles during the test.

The box that houses the control unit is also used to transport the probe, tubing, penetration rods, and necessary accessories (Figure 3). When filled with equipment, the box weighs about 0.5 kN (110 lb) and can be pulled along on its two wheels by one person.

To evaluate the base, subbase, and subgrade of an existing pavement or the subgrade for a new pavement, with the pavement pressuremeter, a hole is made from the surface down to a depth of 2000 mm (78.7 in) by driving a 35 mm (1.38 in) diameter steel rod. Immediately after the steel rod is withdrawn, the short pressuremeter probe is inserted in the hole, and tests are performed every 3000 mm (11.8 in) of depth (Figure 1). The making of the hole takes from 2 to 10 min, and one pavement pressuremeter test takes an average of 6 min. Therefore, a test station that consists of one hole and six tests can be completed in an hour.

A pavement pressuremeter test consists of inflating the probe at a constant rate of strain; both pressure and volume are recorded. An unloading-reloading cycle is performed during each test toward the end of the AB portion of the curve (Figure 2). The pressure and volume readings are corrected for membrane resistance and tubing expansion, respectively (3). The corrected curve is plotted, and two moduli values are calculated, as explained below.

The modulus (E) is obtained from the slope of the AB portion of the test curve (Figure 2) by using the linear elastic, cylindrical expansion theory of Lamé and Poisson's ratio of 0.33 (1). The reload modulus (E_r) is obtained from the reloading portion of the cycle (CD on Figure 2) by using the same assumptions:

$$E = 2.66\, V_m(\Delta p/\Delta v) \tag{1}$$

$$E_r = 2.66\, V_{mr}(\Delta p_r/\Delta v_r) \tag{2}$$

$$V_m = V_c + [(v_o + v_f)/2] \tag{3}$$

$$V_{mr} = V_c + [(v_{or} + v_{fr})/2] \tag{4}$$

where, referring to Figure 2,

$\Delta p/\Delta v$ = slope of AB,
$\Delta p_r/\Delta v_r$ = slope of CD,
V_c = initial volume of the probe = 1.9×10^5 mm³,
v_o = volume injected at A,
v_f = volume injected at B,
v_{or} = volume injected at C, and
v_{fr} = volume injected at D.

The method used to prepare the borehole (driving of the rod) disturbs the soil. This disturbance seems to result in a change in E-value of about 30 percent (2) and seems to be particularly important in silt and loose soils. However, the method of borehole preparation outlined here is recommended in all types of soils for the following reasons: The use of one standard method for all soils avoids errors due to the wrong choice among several recommended methods. Augering, sampling, and selfboring are not feasible because of the small diameter of the hole. The recommended method is simple, fast, and leaves a well-calibrated hole that has smooth sidewalls that rarely cave in. The standardization of the method allows any deviation from an ideal hole to be absorbed in correlations between the test and observed pavement behavior. Other researchers have used similar methods with success (4). Even though disturbance has an influence on the first loading modulus, it has less influence on the reload modulus (E_r). As shown here, the pressuremeter test and the plate test correlate reasonably well. Since preparations for the plate test do not disturb the soil, we can conclude that disturbance involved in the preparation of the hole for the pavement pressuremeter is not a major concern.

CORRELATION WITH A PLATE TEST

McLeod Plate Test

The McLeod plate test is widely used in Canada for the evaluation of airport pavements. When the pressuremeter test is correlated to the McLeod plate test, use can be made of the existing design and evaluation procedures associated with the McLeod test.

The McLeod plate test (5) consists of loading a 762-mm (30-in) diameter steel plate placed on the pavement surface (Figure 4). Usually, a trailer loaded with a huge rubber container filled with water is used as a reaction (Figure 4). The test consists of applying to the plate a load (S) that, repeated 10 times, will cause a 12.5 mm (0.5 in) deflection of the surface at the tenth repetition. If the plate test is performed on the pavement surface, S is the pavement bearing strength (S_p); if performed on the subgrade surface, S is the subgrade bearing strength (S_s).

The subgrade bearing strength (S_s) is the basic design parameter for airport pavements in Canada at the present time. In general, S_s is not measured directly but is deduced from the measurement of S_p. A relation has been established between S_s and S_p (5):

$$S_s = S_p \times 10^{-(t/165)} \quad (5)$$

where t is the equivalent granular thickness of the pavement in centimeters (1 cm of base course equals 1 cm of equivalent granular thickness; 1 cm of asphalt concrete equals 2 cm of equivalent granular thickness).

Testing Program

Pavement pressuremeter tests and McLeod plate tests were performed at two airport sites selected by Transport Canada: Sarnia Airport and Ottawa International Airport.

At Sarnia Airport, the pavement of the main runway is made up of 60 mm (2.4 in) of asphalt concrete and 280 mm (11 in) of moist, medium-sized, sandy gravel. The testing program took place while the runway pavement was being overlaid. After the overlay the total asphalt concrete thickness was about 140 mm (5.6 in). The subgrade is a silty clay that has a natural water content of 13 percent, a liquid limit of 29 percent, and a plastic limit of 15 percent.

Five McLeod plate tests were run along the center line of the runway; S_p was measured and then S_s was calculated. The results are shown in Table 1. The McLeod plate tests at locations (holes) 3, 5, and 6 were performed before the overlay, and tests at 7 and 15 were performed just after the overlay.

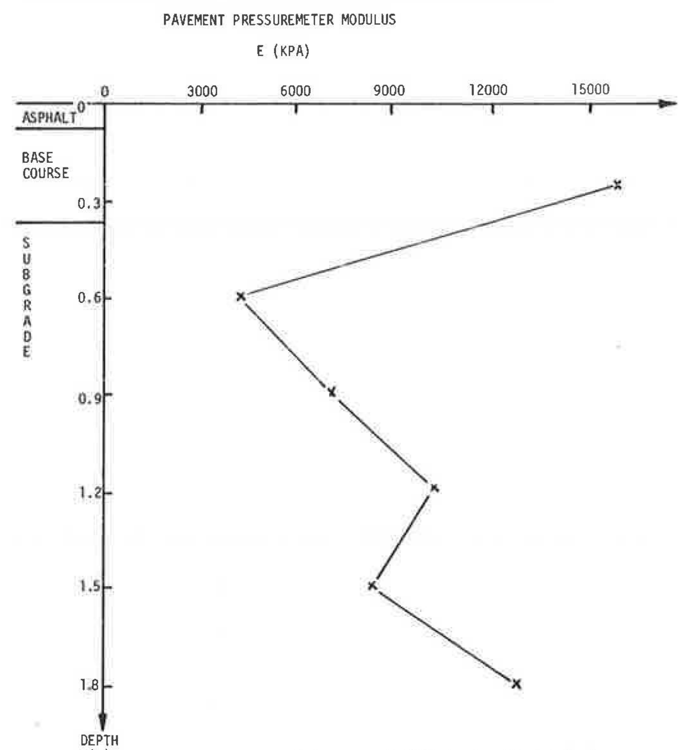
Pavement pressuremeter tests were performed in a total of five holes located a few feet from where the plate tests had been performed. Each hole was prepared by driving the 35-mm (1.35-in) rod to a depth of 1800 mm (6 ft), withdrawing the rod, and then inserting the pressuremeter to the 1800-mm depth. Pressuremeter tests were run at 1-ft intervals from the bottom of the hole up to a depth of 1 ft. For each test, only the first loading modulus (E) was calculated because, at the time of the Sarnia tests, the standard procedure for running a pressuremeter test that involved an unloading-reloading cycle (3) had not been established. Figure 5 shows a typical profile of pavement pressuremeter moduli and Table 2 summarizes the pressuremeter results for Sarnia Airport.

Ottawa International Airport has two parts: an older, smaller airport and a more recent airport. The pavement of the older airport is made up of 50 mm (2 in) of asphalt concrete and 100 mm (4 in) of base course; the subgrade is a moist, uniform, medium-to-fine sand. The pavement of the more recent airport is made up of 100 mm (4 in) of asphalt concrete and 300 mm (12 in) of base course. The subgrade is a dense, silty sand that has 20 percent silt, 60 percent sand, and 20 percent gravel.

Six McLeod plate tests were run at Ottawa International Airport: Two were run on the more recent pavement and four were run on the older pavement. S_p was measured in each case and then S_s was calculated. The results are shown on Table 3. Pavement pressuremeter tests were performed in six holes a few feet away from where the plate tests had been performed. Each hole was prepared and the tests were run as described for Sarnia Airport, with the exception that, at Ottawa International Airport, unloading and reloading cycles were performed. By the time of the Ottawa tests, the standard procedure to run a pavement pressuremeter test (3) had been

Figure 4. McLeod plate test.

Figure 5. Sarnia Airport: pressuremeter modulus profile of hole 7.



Note: 1 m = 3.28 ft; 1 kPa = 0.145 lbf/in².

Table 1. Sarnia Airport: summary of McLeod plate test results.

Hole	Pavement Bearing Strength, S_P (kN)	Base Course Thickness, T_B (cm)	Asphalt Thickness, T_A (cm)	Equivalent Pavement Thickness, T (cm)	Subgrade Bearing Strength, S_S (kN)
3	196	20	5	30	129
5	186	23	7	37	111
6	243	24	6	36	147
7	265	29	14.5	58	118
15	208	24	14.5	53	100

Note: 1 cm = 0.393 in; 1 kN = 0.224 klp.

Table 2. Sarnia Airport: summary of pressuremeter moduli profiles.

	Pavement Pressuremeter Modulus, E (MPa)				
Depth (m)	Hole 3	Hole 5	Hole 6	Hole 7	Hole 15
0.23	6.6	6.4	10.1	16.8	15.3
0.6	1.4	5.8	2.8	4.2	7.5
0.9	2.2	17.9	10.3	7.2	5.6
1.2	7.9	28.2	14.2	10.2	13.1
1.5	9.2	21.2	9.0	8.4	17.8
1.8	7.7	18.2	9.1	12.8	10.5

Note: 1 m = 3.28 ft; 1 MPa = 145.037 lbf/in².

established. Therefore, both E and E_r values are available for the Ottawa tests. Figure 6 shows an E and E_r profile and Table 4 summarizes the pressuremeter results.

Comparison

At each test location, the McLeod plate gives one unique value of S_p, and the pressuremeter gives two profiles of six moduli (Figure 6) [one profile in the case of Sarnia (Figure 5)]. It is the profiles of stiffness that give the pressuremeter test a major advantage over the plate test; the engineer can now see where weak layers exist in a pavement or if soft soil exists over a particular depth in a subgrade. In order to make a comparison between the two tests, the pressuremeter moduli had to be reduced to one average or equivalent modulus by using an appropriate averaging method.

The chosen method involves the following steps:

1. The pavement and the subgrade are divided into layers with the boundary between layers considered to be at the midpoint between two consecutive pressuremeter tests;
2. A pressuremeter modulus is assigned to each layer;
3. The rigid McLeod plate is placed on this multilayer soil, and the plate is loaded with the bearing strength that has been measured in the field;
4. The settlement (s) of the rigid plate is calculated by using multilayer elastic theory and the finite element method (2); and
5. The equivalent pressuremeter modulus is obtained from the formula that gives the settlement of a rigid plate on a linear elastic homogeneous half space:

$$E_e = (\pi/4)(1 - \nu^2)(Q/sB) \tag{6}$$

where

E_e = the equivalent modulus;
ν = Poisson's ratio, considered as 0.33 in all cases;
Q = the load (S_p or S_s depending on the case);
B = the plate diameter [762 mm (30 in)]; and
s = the settlement calculated by using multilayer elastic theory.

A total of four equivalent pressuremeter moduli was calculated. The four are

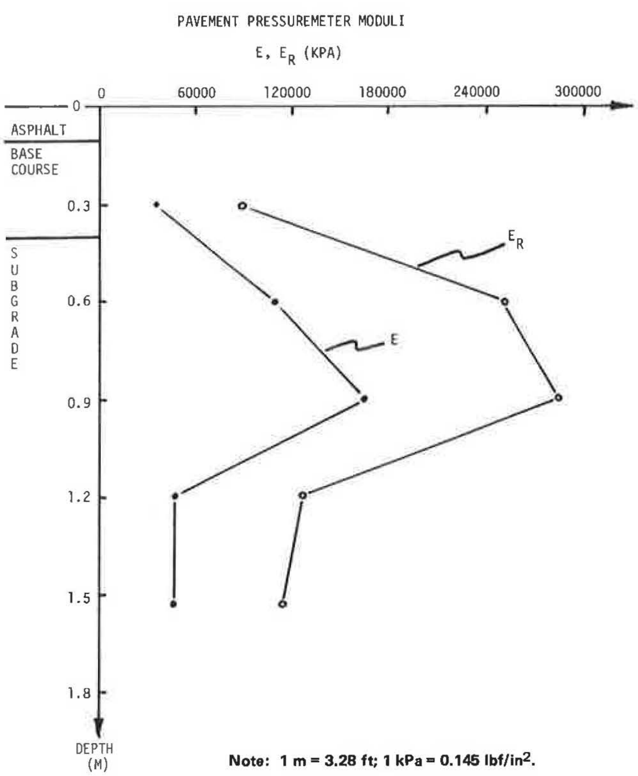
1. The pavement equivalent pressuremeter modulus (E_{ep}), the modulus of a fictitious homogeneous material that is equivalent to the layered pavement and subgrade that have six pressuremeter moduli (E) as layer moduli;
2. The pavement equivalent pressuremeter reload modulus (E_{rep}), the modulus of a fictitious homogeneous material that is equivalent to the layered pavement and subgrade that have six pressuremeter reload moduli (E_r) as layer moduli;
3. The subgrade equivalent pressuremeter modulus (E_{es}), the modulus of a fictitious homogeneous soil that is equivalent to the layered subgrade that have pressuremeter moduli (E) as layer moduli; and

Table 3. Ottawa International Airport: summary of McLeod plate test results.

Hole	Old or New Airport	Pavement Bearing Strength, S_P (kN)	Asphalt Thickness, T_A (cm)	Base Course Thickness, T_B (cm)	Equivalent Granular Thickness, T (cm)	Subgrade Bearing Strength, S_S (kN)
1	New	1709	10	30	50	851
2	New	1728	10	30	50	860
3	Old	412	5	10	20	312
4	Old	405	5	10	20	306
5	Old	601	5	10	20	455
6	Old	614	5	10	20	464

Note: 1 kN = 0.224 kip; 1 cm = 0.393 in.

Figure 6. Ottawa International Airport: pressuremeter modulus profile of hole 7.



Note: 1 m = 3.28 ft; 1 kPa = 0.145 lbf/in².

Table 4. Sarnia Airport: summary of pressuremeter moduli results.

	Pavement Pressuremeter Moduli, E and E_R (MPa)											
	New Airport				Old Airport							
	Hole 1		Hole 2		Hole 3		Hole 4		Hole 5		Hole 6	
Depth (m)	E	E_R	E	E_R	E	E_R	E	E_R	E	E_R	E	E_R
0.25	47.4	114.0	35.4	88.0	17.5	41.2	18.0	65.5	40.2	84.1	21.5	64.2
0.6	27.5	70.0	109.3	251.6	13.9	36.0	16.2	55.8	32.7	78.7	25.6	72.5
0.9	106.9	298.0	163.9	283.8	14.5	41.1	11.3	36.7	13.0	42.0	16.7	55.0
1.2	100.7	224.9	45.9	126.3	4.6	7.3	7.8	19.1	16.6	42.5	11.2	27.4
1.5	64.6	16.6	47.7	110.0	4.1	12.5	8.7	2.1	13.7	34.0	10.4	17.4
1.8					8.4	19.4	9.9	21.4			16.9	33.8

Note: 1 m = 3.28 ft; 1 MPa = 145.037 lbf/in².

Table 5. Equivalent pressuremeter moduli.

	Ottawa International										
	New Airport		Old Airport				Sarnia Airport				
Item	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5	Hole 6	Hole 3	Hole 5	Hole 6	Hole 7	Hole 15
E_{EP} (MPa)	76.5	83.9	15.4	18.0	31.0	24.7	5.1	17.8	12.2	24.1	24.5
E_{REP} (MPa)	160.2	167.1	38.2	51.6	69.9	70.5					
E_{ES} (MPa)									5.7		
E_{RES} (MPa)	105.4				54.3						

Note: 1 MPa = 145.037 lbf/in².

Figure 7. Correlation between plate and pressuremeter: E_{ep} versus S_p.

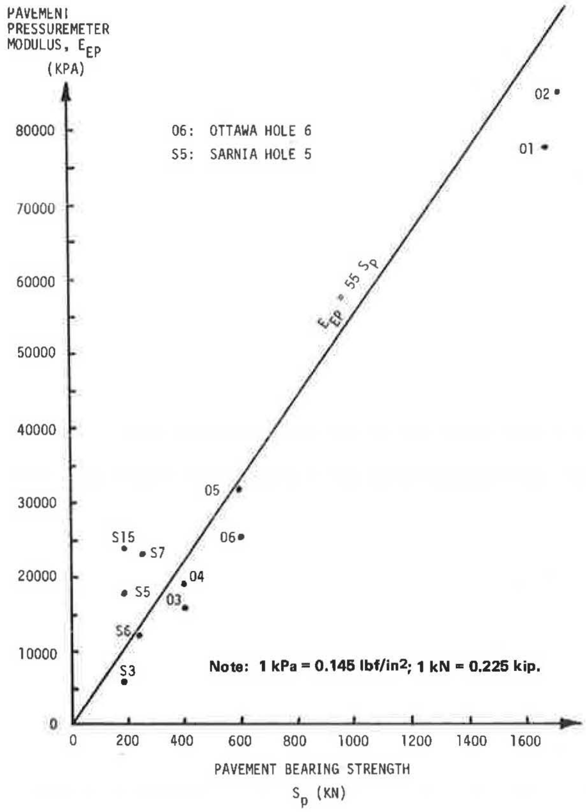
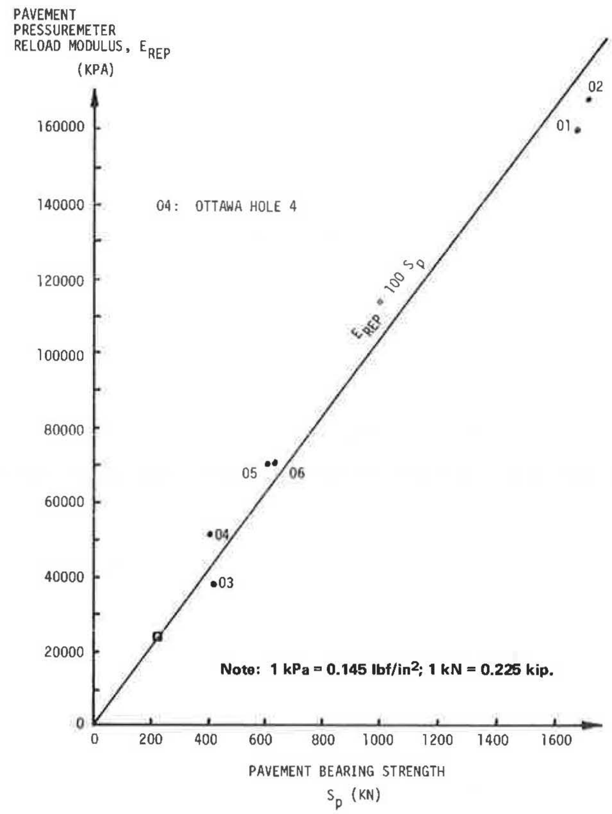


Figure 8. Correlation between plate and pressuremeter: E_{rep} versus S_p.



4. The subgrade equivalent pressuremeter reload modulus (E_{res}), the modulus of a fictitious homogeneous soil that is equivalent to the layered subgrade that have pressuremeter reload moduli (E_r) as layer moduli.

In the case of E_{ep} and E_{rep}, which involve the surface layer of the pavement, a deformation modulus for the asphalt concrete had to be assumed since the probe of the pressuremeter is too long to enable the modulus of the asphalt concrete to be measured. A value of 1.5 million kPa was considered to be reasonable for the asphalt modulus in all cases. The theory required a value of Poisson's ratio for each layer. Since neither the pressuremeter nor the plate test measure Poisson's ratio, a value of 0.33 was simply assumed for all cases. This value is a reasonable average for soils and, in addition, variations in Poisson's ratio usually have a relatively small influence on the magnitude of settlement (6, p. 160; 7).

The moduli E_{ep} and E_{rep} are obtained for the load S_p; E_{es} and E_{res} for the load S_s. A summary of all the equivalent moduli that were calculated for the different test locations at Sarnia and Ottawa International Airports is given in Table 5.

Correlations

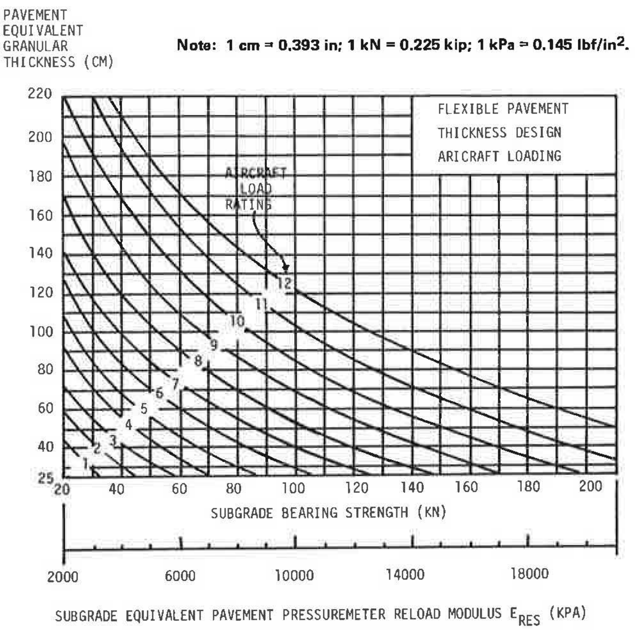
Figure 7 presents a plot of E_{ep} versus S_p, and Figure 8 presents a plot of E_{rep} versus S_p. In both cases it seems reasonable to represent the test results by straight lines, as shown, where

$$E_{ep} = 55\ S_p \tag{7}$$

with E_{ep} in kilopascals and S_p in kilonewtons, and

$$E_{rep} = 100\ S_p \tag{8}$$

Figure 9. Design chart for flexible airport pavement by using pavement pressuremeter.



Referring to Figure 7, the scatter in results is appreciable for low values of E_{ep} and S_p (Sarnia Airport). This large scatter may occur because the soil is fine grained and would be disturbed somewhat when the boreholes are made. The large scatter may also be because the plate test and pressuremeter test results were not as reliable in Sarnia as in Ottawa. In Sarnia there were calibration problems with the jack that was used for the plate tests, and the operators for the pressuremeter tests were inexperienced.

The scatter in values is small in Figure 8. One reason for the limited amount of scatter is that there are no points shown for Sarnia Airport because the reload modulus (E_r) was not measured. An average value of E_r for Sarnia can be estimated as follows: E_r was measured in one test in Sarnia, and for that test the ratio E_r/E was 1.4; given that the average E_{ep} value for Sarnia is 16 700 kPa, then an estimate of the average E_{rep} is 16 700 x 1.4 = 23 380 kPa. The corresponding average S_p value is 220 kN. This point is represented by a square on Figure 8.

Figures 7 and 8 tend to prove that there is a simple correlation between McLeod plate test results and pavement pressuremeter test results. It seems reasonable to assume, therefore, that the empirical design rules for flexible airport pavements based on the McLeod plate test can be employed equally successfully by using the pressuremeter test.

CHART DESIGN

Engineers are familiar with the chart approach to pavement design, so little needs to be said here concerning the method. For the purpose of demonstration only, the empirical chart method employed by Transport Canada is used in this section because we are most familiar with this procedure.

Canadian Design

The design of new flexible airport pavements is carried out in accordance with Transport Canada manual AK-68-12 (8):

1. The subgrade of the airport site is classified according to the Unified Soil Classification System; the subgrade bearing strength (S_s) is estimated from the subgrade classification;
2. The design plane that will be landing at the airport site is classified according to its aircraft load rating (ALR); the ALR is a number that ranges from 1 to 12; for example, the ALR is 12 for a Boeing 747 or a Concorde, but it is 1 for very small planes;
3. Once S_s and the ALR are known, Figure 9 is used to find the equivalent granular thickness (t) of the pavement; t takes into consideration the equivalency factors for various components of the pavement;
4. The pavement is then designed to have the minimum required thickness of asphalt, the minimum required thickness of base course, and the remaining portion of t in subbase; these minimum requirements depend on the maximum tire pressure;
5. Once the pavement is built, a number of McLeod plate tests are carried out; the tests generate pavement bearing strength parameters (S_p); and
6. At any one plate test location, a new S_s value is deduced from the S_p value by using Equation 5; the S_s values are multiplied by a reduction factor, if necessary, to account for a loss in strength during the thawing of frozen ground in the spring of the year; the lower quartile adjusted S_s value is determined and is considered to be the applicable in situ S_s value; comparison of this S_s value with the design S_s value from step 1 provides the engineer with a check on the design.

In Canada, the evaluation of existing pavements is carried out as follows:

1. A number of McLeod plate tests are performed on the pavement, which gives rise to a number of S_p values; the corresponding S_s values are obtained by using Equation 5.
2. As is done during the design of new pavements, the S_s values are multiplied by a spring reduction factor, if necessary. The lower quartile adjusted S_s value is determined and is considered to be the applicable in situ S_s value.
3. The ALR of the design plane is obtained, and, by using the thickness design chart of Figure 9, the required value of t is determined.

If the existing t is greater than the required t, the pavement is satisfactory. If the opposite is true, the pavement needs to be strengthened, and the thickness of the necessary overlay is deduced from the difference between the required and existing t-values.

Pavement Pressuremeter Design

The design chart of Figure 9 is based on S_s values that are either assumed (initial design) or calculated from plate-bearing tests. A similar chart can be produced based on pressuremeter modulus values by making use of the plate-pressuremeter correlation equations that were deduced from the research program outlined in this paper. E_{rep} is considered to be a more reliable parameter than E_{ep} for this purpose because E_{rep} is less influenced by disturbance to the soil than is E_{ep} and the fit between E_{rep} and S_p is better than that between E_{ep} and S_p. Equation 8 is a relation between S_p and E_{rep}, and it seems reasonable to assume that the same relation holds between S_s and E_{res}. On Figure 9 an E_{res} axis has been added that allows flexible airport pavements to be designed on the basis of pressuremeter moduli.

The following procedure can be followed to design new airfield flexible pavements on the basis of pressuremeter test results.

1. Pavement pressuremeter tests should be performed in the subgrade at regular intervals along the proposed runway. This represents a considerable advance over the existing method because the actual deformation properties of the subgrade are measured rather than chosen based on a soil classification. The test holes should be spaced about 100 m (300 ft) apart, and at each hole location a test should be performed every 0.3 m (1 ft) of depth down to 1.5 m (5 ft).
2. The modulus (E_r) should be calculated for each test, and an E_r profile obtained for each location.
3. The subgrade equivalent pressuremeter reload modulus (E_{res}) should be calculated for each test-hole location. In order to do this, a fictitious, but reasonable, subgrade bearing strength (S_s) has to be chosen to calculate s by using multilayer elastic theory. An S_s value of 100 kN (~20 000 lb) is recommended. Because of the superposition law of linear elasticity, the value of S_s has no influence on the E_{res} value, which is calculated. If the required computer program is not available, an approximate value of E_{res} can be obtained by using the following formula:

$$1/E_{res} = (1/100)\,[(22.1/E_1) + (33.5/E_2) + (24.6/E_3) + (14.8/E_4) + (5/E_5)] \qquad (9)$$

where E_1 is the reload modulus obtained at the shallowest depth in the subgrade. E_2, E_3, E_4, and E_5 are the reload moduli obtained at a depth of 1 ft below, respectively, E_1, E_2, E_3, and E_4. This formula was obtained by assuming a single average vertical strain distribution below the plate (2). Incidently, correlation between pressuremeter and plate results by using this approach presents much less scatter than in Figure 7.
4. The E_{res} values are multiplied by the applicable spring reduction factor, and the lower quartile factored E_{res} value is determined. The lower quartile E_{res} is considered to be the design in situ E_{res} value.
5. ALR of the design plane is obtained. The in situ E_{res} and the chart of Figure 9 are used to determine the required equivalent granular thickness (t_1).
6. If base-course material is available from different borrow pits, it may be desirable to prepare pavement test sections with the different base-course materials and to test them with the pressuremeter.

For the evaluation and design of overlays for existing pavements, the following procedure should be followed:

1. Pavement pressuremeter tests should be performed at regular intervals along the runway. At each hole location, a test is performed immediately below the asphalt layer, and subsequent tests are performed at 0.3-m (1-ft) intervals down to a depth of about 1.8 m (6 ft). The test holes should be about 100 m (300 ft) apart.
2. The modulus (E_r) should be calculated for each test, and an E_r profile obtained for each location.
3. Only the results of tests in the subgrade should be considered for use with the design chart (Figure 9), but the tests in the base and subbase are of considerable value because they allow the engineer to assess directly the competence of thin layers in the make-up of the pavement. The subgrade equivalent pressuremeter reload modulus (E_{res}) for each test-hole location should be calculated from the subgrade pressuremeter tests by following step 3 of the new pavement design procedure.
4. Follow step 4 of the new pavement design procedure.
5. Follow step 5 of the new pavement design procedure.
6. This required thickness (t_1) is compared with the equivalent granular thickness of the existing pavement (t_2). An overlay is necessary if t_1 is greater than t_2; the overlay thickness is

$$t\,(\text{overlay}) = (t_1 - t_2)/\text{equivalency factor} \qquad (10)$$

The above design procedure points out two advantages of the pressuremeter test over the plate test. The first advantage is that pressuremeter tests can be carried out in situ before the pavement is designed and built in areas where it would be impractical to carry out plate tests. Real deformation values are then available for design rather than estimated values. The second advantage is that, even with the pavement in place, the subgrade modulus is measured directly by the pressuremeter, whereas with the McLeod procedure the subgrade bearing strength (S_s) is estimated from the pavement bearing strength (S_p) by means of Equation 5.

MULTILAYER ELASTIC DESIGN

The alternative to the empirical chart route to pavement design and evaluation is the use of elastic theory.

Existing Procedures

In the multilayer elastic design, the pavement-subgrade system is considered to be a multilayer elastic continuum. Each layer is characterized by a modulus of elasticity and a Poisson's ratio. The strains generated in the multilayer elastic continuum by the load from the design aircraft are calculated by using a computer program. Two strains are considered to be critical: the maximum horizontal tensile strain (ε_H) at the lower face of the asphalt layer and the maximum vertical compressive strain (ε_V) at the top of the subgrade. The design asphalt and pavement thicknesses are the thicknesses that are required to ensure that the magnitudes of ε_H and ε_V are within acceptable limits, called the limiting strain criteria.

The multilayer elastic theory approach to pavement design is coming into greater use. The evaluation of the moduli of deformation for the various pavement layers has not kept pace with the rapid advance in theory and computational capabilities. A number of ways exist to estimate the necessary moduli, including a correlation between California bearing ratio (CBR) and deformation modulus and triaxial tests on prepared samples, but none of the ways are direct in the sense of measuring actual in situ deformation properties. In this regard, the pavement pressuremeter test represents a real improvement because of its ability to measure deformation moduli in situ.

Pavement Pressuremeter Procedure

For both Sarnia and Ottawa International Airports, the strains ε_H and ε_V were calculated by assuming the pavements to be loaded with the respective design plane: the Convair 440 for Sarnia Airport, the DC-8-63 for the new section of Ottawa Airport, and the DC-3 for the older section of Ottawa Airport. The Poisson's ratio for all layers was assumed to be 0.33 (7). An asphalt modulus of 1.5 million kPa (≈200 000 lbf/in²) was assumed to be a reasonable value. The base course, subbase, and subgrade were divided into layers that have boundaries at the midpoint between two consecutive pressuremeter tests. The pressuremeter reload moduli (E_r) were considered to be the applicable moduli of elasticity of each layer. Since E_r was not measured at Sarnia Airport, an estimate of the E_r value of each layer was obtained by averaging the E values of holes 5, 6, 7, and 15 and then simply doubling the resulting E values. For Ottawa International Airport, the E_r values for each layer were obtained by averaging the E_r values of holes 1 and 2 for the newer section and of holes 3, 4, 5, and 6 for the older section. This selection process led to one profile of elastic constants being made available for each of the three pavements.

The computer program bitumen-structures-analysis-in-roads (BISAR) (7) was used to calculate ε_H, ε_V, and the maximum pavement deflection (s) under the load of one leg of the design airplane. The results are shown in the table below (1 mm = 0.039 in):

Item	Ottawa International New Airport	Ottawa International Old Airport	Sarnia Airport
Design plane	DC 8-63	DC-3	Convair 440
Asphalt strain, H	0.001 66	0.000 81	0.000 44
Subgrade strain, V	0.003 04	0.003 1	0.003 03
Settlement, s (mm)	3.9	3.1	2.2

A reasonable estimate of the activity at the two airports is 5000 landings and takeoffs of the design plane per year. Given this level of activity and the properties of most asphalts, the limiting strain in the asphalt can be assessed at 0.0011 (7). A limiting subgrade strain can also be assigned depending on the level of activity at the airport (9). For cases being considered here, the limiting subgrade strain would be of the order of 0.002. These limiting strain criteria mean that if the asphalt strain (ε_H) is 0.0011 of less and if the subgrade strain (ε_V) is 0.002 or less, under the static load of the design plane, the pavement will perform satisfactorily for at least 5000 passes of the design plane.

If we compare the calculated strains (see table above) with the limiting strains, we can see that (a) the calculated strains are not far from the limiting strains and (b) the calculated strains for the subgrade are somewhat higher than the subgrade limiting strain. This comparison would imply that the future performance of the pavements is questionable. Given that the pavement at Sarnia Airport had just been overlaid at the time of testing and that the pavements of Ottawa International Airport are in excellent condition, the future performance of the pavements does not really seem to be questionable. A more logical conclusion is that the use of the pressuremeter modulus (E_r) in multilayer elastic design is not compatible with the use of the established limiting strain criteria. In this instance, E_r values are too small, which results in calculated strains that are too large.

Even though the E_r values are measured during a reload cycle, they are measured over an average of 4 percent volumetric strain. Continuing research on the subject shows that much higher E_r values are obtained at lower strain levels and that even an initial tangent modulus can be obtained with the pavement pressuremeter. The choice then is between (a) continuing to use E_r values measured over 4 percent strain and establishment of more-appropriate limiting strain criteria by direct calibration with pavement performance or (b) keeping the established strain criterion and selection of E_r values at a more appropriate (smaller) strain level. The second solution is favored and will be the subject of further discussion in another article.

ADVANTAGES AND DISADVANTAGES OF THE PAVEMENT PRESSUREMETER METHOD

Disadvantages of the pavement pressuremeter method include that the test requires a 35-mm (1.38-in) diameter hole through the pavement. This does not seem to be a major drawback because a hole of this size can be backfilled and patched easily. The pressuremeter loads the soil laterally, not vertically as does a wheel. This criticism is not as serious as it may appear because (a) pressuremeter tests have been carried out in both vertical and horizontal boreholes in a wide range of soils, and the results show that the horizontal and vertical moduli are within a few percent of each other (1) and (b) support for the wheel of a truck or a plane does not come only from vertical soil reaction but from horizontal soil reaction as well. The pavement pressuremeter cannot measure, as yet, a modulus E_r in the thin asphalt layer.

Some of the advantages of the pavement pressuremeter method are that the apparatus is relatively inexpensive and is available commercially. It is portable and a test is relatively quick. The quality of a test can be evaluated from the shape of the pressure-volume curve; the engineer can therefore develop a level of confidence in the results. The average magnitude of the six moduli measured at each station allows an assessment to be made of the overall pavement stiffness, although the profile of moduli indicates the variation of pavement stiffness with depth and can be used, for example, to single out a weak layer. The test can be used not only for the evaluation of existing pavements and the design of overlays but also for the design and control of new pavements. The pressuremeter moduli are sound input parameters for the multilayer elastic theory.

Other potential uses of the pavement pressuremeter include the selection for strength of base-course materials, the determination of equivalency factors, the determination of subgrade reaction value for the design of rigid pavements, the control of compaction, and the determination of the plastic properties of each layer by repeating the inflation-deflation of the probe a number of times.

CONCLUSIONS

A new pressuremeter and test method have been described that show promise for pavement design. The equipment is compact, sturdy, and can be easily carried by two people. The test procedure is simple, the test is of short duration, and the results are reproducible.

Each test yields a modulus of deformation for the soil, and a moduli profile is obtained at each test station. A total of 93 pavement pressuremeter tests and 11 McLeod plate tests were run in parallel at two airports in Canada. The McLeod plate test is the test that is used by Transport Canada for the design of flexible airport pavements. The pavement pressuremeter was shown to have definite potential for the design of airport pavements by showing that a correlation exists between pavement pressuremeter test results and McLeod plate test results. This correlation was used to generate a design procedure based on the pavement pressuremeter and a simple chart (Figure 9). This chart was obtained by replacing the McLeod plate parameters by an equivalent pressuremeter parameter in the well-established Transport Canada design chart (Figure 9).

The multilayer elastic design method makes a more thorough use of the moduli profile obtained with the pavement pressuremeter than does the chart design procedure. The multilayer elastic design is therefore recommended. In the examples quoted in the text the calculated strains were probably larger than they should be. The overestimation of strain was attributed to the fact that the pressuremeter modulus is measured at strain levels that are larger than the strains developed by the wheel load. Recently a means of obtaining pressuremeter moduli at much lower volumetric strains has been devised, and the method will be the subject of another article.

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Load Equivalency Factors of Triaxle Loading for Flexible Pavements

M.C. WANG AND R.P. ANDERSON

This paper presents the load equivalency factors of triaxle loading for flexible pavements. Two different approaches were used to determine load equivalency factors—American Association of State Highway Officials' (AASHO) empirical and mechanistic approaches. AASHO's empirical approach was used first to determine the load equivalency factor of 338-kN (76-kip) triaxle loading. For this approach, experimental pavements were subjected to approximately 55 000 repetitions of 338-kN triaxle loading. The load equivalency factor determined was 2.60 for the range of structural numbers studied and for a terminal serviceability index of about 2.0. The mechanistic approach was used in order to include a broad range of triaxle loading intensity. For this approach, the maximum vertical compressive strain on the top of the subgrade was analyzed by using the bitumen-structures-analysis-in-roads (BISAR) computer program. The maximum subgrade compressive strains were related with load equivalency factors in logarithmic coordinates for single- and tandem-axle loadings. The relation for triaxle loading was established by first plotting the equivalency factor determined from the AASHO approach against the maximum subgrade strain. Then a line was drawn through this point parallel to the lines of single- and tandem-axle loads. The load equivalency factors of various triaxle loading intensities were then obtained by entering the maximum subgrade strain of each load intensity into the relation.

One of the most important tasks of highway officials and engineers is the maintenance of the deteriorating, existing highway system. The deterioration of the highway network is augmented by the continued growth of traffic and the accompanying increase in vehicle size and gross weight in an attempt to improve the energy savings and economic efficiency of the transportation system. In order to maintain the heavy gross vehicle weight and still stay within legal axle-to-axle load restrictions, the trucking industry has devised the triaxle or triple-axle configuration. The most common adaptation of this new axle arrangement is the rear assemblage of the familiar single-unit, four-axle coal trucks, although five-axle tractor-semitrailer units that have triaxle configurations are becoming more commonplace.

Highway engineers are concerned about the impact of the innovative heavy triaxle vehicles. Unfortunately, results of the American Association of State Highway Officials (AASHO) road test (1) do not include information that would permit an assessment of the structural damage caused by triaxle vehicles. Consequently, incorporation of triaxle loading into design formulas is not possible. Additional work is necessary to determine the relative destructive effect of heavy triaxle configuration and allow for its application to pavement design and rehabilitation schemes.

One method of assessing the destructive effect of triaxle loading is through the use of the concept of load equivalency factor. The load equivalency factor of a given axle loading is defined as the number