

# Permanent Deformation for Flexible Airfield Pavement Design

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The total permanent deformation of flexible airfield pavements is one of the best indicators of the overall performance of the pavement system. A methodology was developed to predict this distress mode under aircraft loadings on asphaltic concrete pavement systems. Particular emphasis is placed on the use of lateritic gravels intrinsic to many parts of Brazil. Using dynamic triaxial tests in the laboratory, models based on the California bearing ratio, state of stress, and number of load repetitions were developed for estimating the resilient modulus and the plastic deformation of lateritic base, subbase, and subgrade layers. The permanent deformation for flexible airfield pavement design (PDAPD) computer model was developed from modification of the existing Asphalt Institute DAMA program on the basis of multilayer elastic theory. The input variables necessary for this model come from three broad areas: the environment, the dynamic characteristics of the materials, and the traffic analysis. PDAPD, which can analyze up to 10-layer pavement structures, estimates the pavement damage on a monthly basis considering three criteria: fatigue of asphalt concrete layers, subgrade deformation, and total permanent deformation of the pavement. General verification of the PDAPD was accomplished by a computer analysis of numerous flexible-pavement airfield structures, designed in accordance with the FAA method. Although individual pavement section results varied, a good overall comparison in design life prediction occurs between the empirically based FAA approach and the mechanistic PDAPD model.

In the past 15 years, significant advancements have been made in knowledge of the permanent strain behavior of pavement layer materials, on the basis of dynamic laboratory tests as well as actual field behavior of the overall pavement system.

There is no doubt that permanent deformation is one of the major indicators of the overall performance of flexible pavements. In highways, where traffic is channelized, permanent deformation is generally characterized by rut depth magnitude. In airfield pavements, where aircraft traffic is distributed more laterally, the variability of permanent deformation of the pavement layers contributes to an increased roughness of the pavement surface.

Historically, initial mechanistic approaches for design of flexible pavement used two distress criteria: (a) limiting the tensile strain at the bottom of the asphalt concrete (AC) layer for repetitive load fatigue cracking and (b) limiting the compressive strain at the top of the subgrade layer to control permanent deformation. The latter criterion permits an estimation of the number of traffic load repetitions that would cause a certain amount of permanent deformation of the subgrade and, consequently, the pavement itself, assuming no deformability occurs within the pavement structure.

If a smooth runway roughness profile (relative to a standard for new construction or runway restoration) and a critical runway roughness profile (for the same pavement structure after a certain number of traffic load repetitions) are known, the difference between those two profiles is caused by the development of the total permanent deformation of the pavement system (1).

Several major pavement design organizations and methods recommend a minimum California bearing ratio (CBR) value of 80 or more for flexible airfield pavement base course materials. Although this specification is appropriate in geographic areas possessing adequate aggregate resources, it is a serious constraint and can greatly increase the costs of pavement construction when specification-quality materials are not available near the work site but adequate supplies of non-specification aggregates are locally present.

This situation is common in some areas of Brazil, where lateritic gravels are the main source of granular materials for base course. Frequently, these deposits do not meet minimum CBR specifications of base and subbase course use, but they have been used successfully in a wide variety of airfield pavements serving DC-9 and B-727 commercial traffic as well as a wide variety of military jet fighter aircraft (2).

The major objective of this study was to develop a methodology using the prediction of total permanent deformation as a major criterion for analyzing and designing airfield flexible pavements. In order to accomplish this goal, two major tasks were accomplished:

1. A comprehensive laboratory evaluation of the repeated load dynamic behavior of lateritic soils from Brazil relative to their resilient (elastic) and plastic behavior, and
2. The development of a computerized analytical pavement analysis program that would be able to consider (a) the non-linear modulus response of these lateritic granular and subgrade pavement materials, (b) the climatic impact (because of high temperature and moisture) on pavement life as a consequence of changes of the in situ response of the pavement materials, and (c) the integration of the plastic deformation prediction of all pavement layers on the basis of a finite time interval (i.e., monthly).

## THE MODEL

### Model Background

The computerized permanent deformation for flexible airfield pavement design (PDAPD) model is represented by the flow chart shown in Figure 1 (3). The model was developed on the

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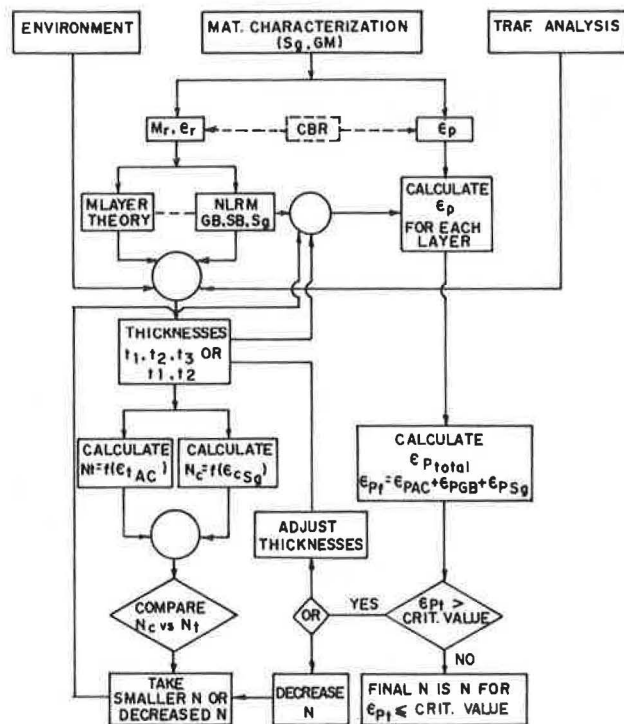


FIGURE 1 PDAPD model.

basis of a modified version of the DAMA computer program, developed by Witczak for the Asphalt Institute. The DAMA program was modified to incorporate nonlinearity of granular and subgrade materials, climatic condition in terms of temperature and moisture content of the pavement materials, and the prediction of permanent deformation for each pavement layer and sublayer, as well as the total pavement deformation.

Like the DAMA program, PDAPD analyzes a multilayered elastic pavement structure considering the cumulative damage for a dual wheel load system in three radial positions: (a) underneath the center of one tire, (b) at the edge of the tire, and (c) between tires.

The program calculates principal and bulk stresses, as well as strains at the surface and bottom of asphalt layers and at the mid depth of each granular and subgrade layer, except for the last subgrade layer, which is assumed to have an infinite thickness. The stresses and strains are calculated at the top of this layer.

The PDAPD program can accommodate one or more AC layers, four granular layers, and five subgrade layers. If the number of AC layers is larger than one, the summation of the number of these layers plus the granular layers must be less than or equal to five. In other words, the program is able to analyze up to 10 layers and sublayers.

### Layer Moduli

#### Asphalt Layer Dynamic Modulus

The PDAPD computer program calculates the dynamic modulus for the asphalt layers considering the asphalt mixture characteristics, air temperature, and pavement temperature

for each month, according to a predictive equation developed by Witczak (4).

#### Granular and Subgrade Layer Resilient Modulus

An extensive laboratory program to evaluate resilient and plastic responses of several lateritic gravels was conducted. In addition, a comprehensive set of compaction and CBR tests was done. Using these results, multiple stepwise regression analyses were conducted for six CBR levels (18.8, 28.8, 38.7, 43.5, 71.6, and 93.0 percent), five levels of confining pressure (3, 5, 10, 15, and 20 psi), and seven layers of deviator stress (3, 5, 10, 15, 20, 25, and 50 psi). Because it was not possible to mold or test specimens at all factorial levels, the final sample size was equivalent to 149 points of observation (5).

The best model, which has been incorporated in the PDAPD program, is as follows:

$$M_R = \frac{179.0412(\text{CBR})^{1.08774}(\theta)^{1.43833}}{(\sigma_1)^{1.18598}} \quad (1)$$

$$(R^2 = 0.92; \text{SEE} = 0.082)$$

where

- $M_R$  = resilient modulus (psi),
- CBR = California bearing ratio,
- $\theta = \sigma_1 + \sigma_2 + \sigma_3$ , the bulk stress or first invariant of stress (psi), and
- $\sigma_1$  = major principal stress (psi).

The CBR variable explains 68.5 percent of the total variation in this model, whereas the inclusion of bulk stress ( $\theta$ ) and the major principal stress ( $\sigma_1$ ) variables in the model increases the explained variation by 9.2 and 14.3 percent, respectively.

All of the nonlinear modulus calculations are done monthly using an iterative approach. The initial seed relationships used to start the stress-dependent moduli solutions are  $1,300 \times \text{CBR}$  and  $400 \times \text{CBR}$ , respectively, for base-subbase and subgrade layer-sublayer materials. With these initial seed values, the bulk stresses and major principal stresses are calculated for each unbound layer as shown in Figure 2.

On the basis of these stresses, new resilient moduli are calculated and compared with the previous values. If the absolute difference between the previous and current resilient modulus is larger than 5 percent, new values are assigned by taking the average between them. This procedure is repeated until the difference between the previous and the new resilient modulus is less than 5 percent for all layers. As previously noted, this process is repeated for each time increment (month) used in cumulative damage analysis. For each time interval, temperature and, hence, stiffness changes of the asphaltic layer occur. Thus, for each time period, the pavement stress states (i.e., moduli) vary.

#### Permanent Deformation

The bulk stress and the major principal stresses calculated from the final moduli iteration are then used to calculate the

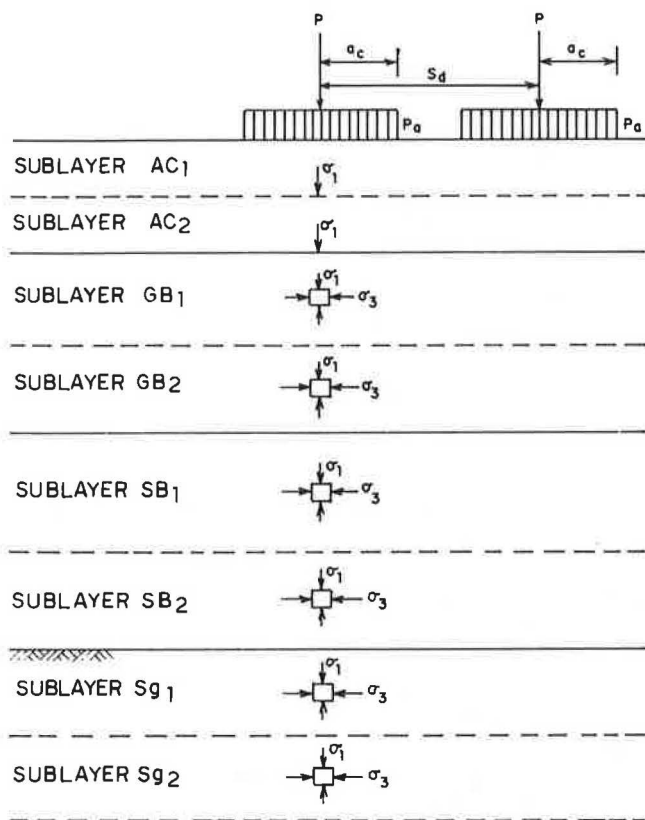


FIGURE 2 Pavement layers and sublayers for resilient and permanent deformation calculation.

permanent strain for each layer (using the monthly repetition level) according to the following equations. These equations were developed from a statistical multiple regression analysis of laboratory test results on the repeated load permanent deformation behavior of the lateritic materials. In this study, the most accurate approach was obtained by developing two separate plastic strain predictive models for CBR values greater than and less than 40 percent.

$$\epsilon_p = \frac{128,748(N)^{0.1346}(\sigma_1)^{2.664}}{(CBR)^{5.55}(\theta)^{1.1431}} \quad CBR > 40 \quad (2)$$

$$\epsilon_p = \frac{(N)^{0.1878}(\sigma_1)^{6.0911}}{55.6313(CBR)^{1.3605}(\theta)^{4.893}} \quad CBR < 40 \quad (3)$$

where  $\epsilon_p$  is the plastic strain (in./in.) and  $N$  is the number of stress repetitions.

Equations 2 and 3 have regression statistics of  $R^2 = 0.741$  and  $0.882$  and  $SEE = 0.245$  and  $0.171$ , respectively (5). In both equations, the most important variable is the CBR, followed by the major principal stress ( $\sigma_1$ ), number of stress repetitions ( $N$ ), and bulk stress ( $\theta$ ). The permanent deformation damage model used for the asphalt layer in PDAPD is

$$\Delta h_{ac} = 4.49\delta(N)^{0.25} \quad (4)$$

where  $\Delta h_{ac}$  is the permanent deformation in the asphalt layer (in.) and  $\delta$  is the elastic deformation (compression) within the asphalt layer itself (in.).

## Distress and Life Predictions

The total predicted permanent deformation for the first month is obtained by accumulating the plastic deformation for each unbound layer (i.e., base, subbase, and subgrade) obtained as a function of CBR, bulk stress, and major principal stress for that particular month. This deformation is added to the predicted rutting within the asphalt layer. For the next month, the accumulation of plastic deformation for each unbound layer is the total permanent deformation estimated for the first 2 months (with CBR and state of stress for the second month) minus the amount of plastic deformation predicted, at the same conditions, for the first month. This process is continued until one of the following conditions occurs:

- For both fatigue fracture and deformation (subgrade strain criteria), the predicted pavement life is computed in months for a given airfield pavement system. The analysis is terminated at 240 months (20 years) if both criteria have predicted lives greater than this threshold value.
- For prediction of total permanent deformation, failure is assumed to occur when a permanent deformation of 1.22 in. (31.0 mm) is obtained. This failure level has been determined from several roughness studies conducted at Brazilian military airfields (1,6,7).

The computer output for total permanent deformation and the accumulated plastic deformation for each layer of material are presented in units of millimeters and inches.

## PDAPD MODEL VERIFICATION

### General Approach

Because verification through field tests was beyond the scope of this initial study, the general philosophy used was to analyze and compare performance for pavement structures designed in accordance with the FAA procedure (8). An investigation was conducted of the effect of several variables—thickness of AC (tac), granular base CBR ( $CBR_{gb}$ ), subbase CBR ( $CBR_{sb}$ ), and subgrade CBR ( $CBR_{sg}$ )—on the resilient modulus ( $M_R$ ) of the unbound layers, the predicted pavement life, and the plastic deformation of each pavement layer.

The pavement structures were designed by the FAA procedure for a B-727-100 aircraft having the following gear characteristics: 166-psi tire pressure, 34-in. dual spacing, and 38,500-lb wheel load. Pavement designs were considered for three levels of repetitions (20-year design): 60,000, 120,000, and 300,000. Table 1 presents the FAA pavement structures used to study the effect of thickness of AC on several variables. A total of 65 cases of pavement structures designed according to the FAA procedure were analyzed with the PDAPD model.

### Resilient Modulus Studies

As previously noted, one study phase dealt with the influence of several layer properties on the predicted nonlinear  $M_R$  response of various layers generated by PDAPD within the FAA-designed structures. In all computer studies, the subgrade was subdivided into five sublayers with the last sublayer being of infinite thickness. The asphalt mixture characteristics, as

TABLE 1 FAA PAVEMENT STRUCTURES STUDIED

Subgrade CBR (%)	FAA Design Repetitions (N)	Thickness - inches					
		AC = 4"		AC = 5"*		AC = 8"***	
		GB	SB	GB	SB	GB	SB
5	60,000	11.0	22.0	11.0	22.0	5.4	22.0
	120,000	12.0	23.0	12.0	23.0	6.0	23.7
	300,000	13.0	25.0	13.0	25.0	6.0	27.4
10	60,000	11.5	8.5	11.5	8.5	5.9	8.5
	120,000	12.0	9.0	12.0	9.0	6.0	9.7
	300,000	13.0	9.5	13.0	9.5	6.0	11.9
15	60,000	11.0	3.5	11.0	3.5	5.4	3.5
	120,000	12.0	3.0	12.0	3.0	6.0	3.7
	300,000	13.0	3.0	13.0	3.0	6.0	5.4

Notes: (\*) AC thickness increased by 1" without substitution of other layer materials.

(\*\*) Granular base thickness set close to 6.0" and substitution ratios of 1.4 used between AC and Granular Base; 1.7 between Granular Base and Subbase.

well as the air and pavement temperatures, were kept constant to approximate the relatively uniform, warm climatic conditions in many areas of Brazil. The conditions selected resulted in a constant AC modulus of approximately 250,000 psi.

#### Influence of AC Thickness

In order to assess the influence of the asphalt thickness on layer  $M_R$ , thicknesses of 4 and 8 in. were investigated. These studies were made at three levels of subgrade CBR (5, 10, and 15 percent) using a subbase CBR of 20 percent and a base CBR of 100 percent. These results are shown in Figure 3.

The higher the subgrade CBR, the higher the resilient modulus for the granular base with a 4-in. AC surface. However,

the resilient modulus of the granular base decreases with an increase of the subgrade CBR when the thickness of AC is increased to 8 in.

This finding can be explained relative to the nonlinear relationship noted in Equation 1. For lower subgrade CBR values and thicker AC layers, the major principal stress decreases significantly when the bulk stress (or confining pressure) is increased. This variation in the level of stress contributes to the increasing resilient modulus in that particular layer for low CBR values. However, when the subgrade CBR is increased, the level of vertical stress increases at the base course layer, which overcomes the influence of bulk stress (or confining pressure) resulting in a lower resilient modulus for the base layer.

Considering the resilient modulus for the subbase and subgrade layers, there are no significant changes caused by

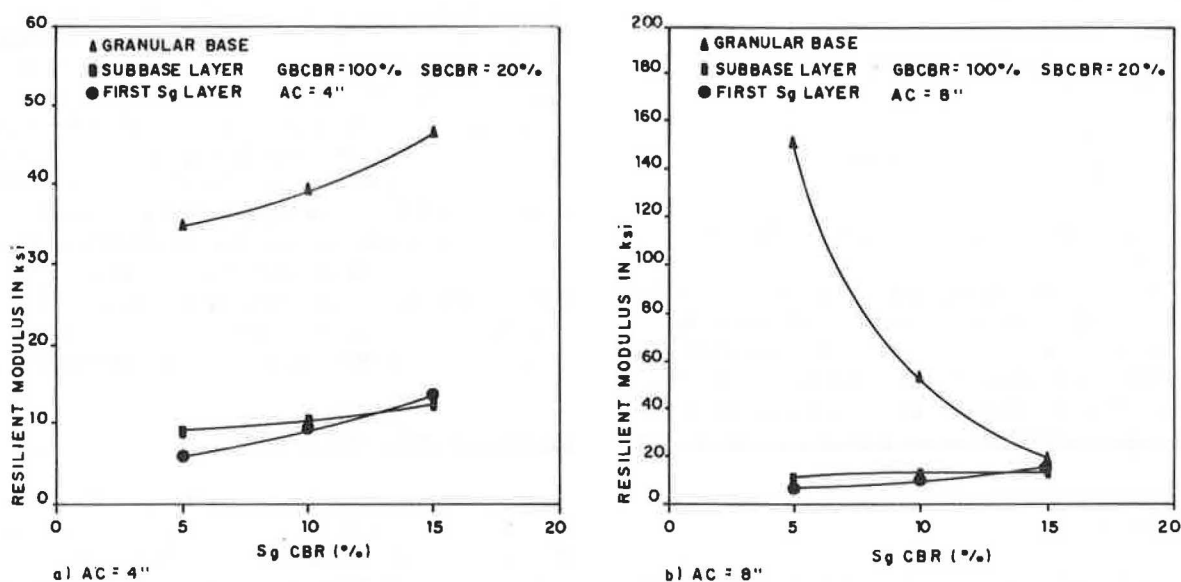


FIGURE 3 Effect of AC thickness on resilient modulus (design according to FAA procedure for 60,000 repetitions).



varying the asphalt thickness from 4 to 8 in. In other words, the resilient modulus of the granular base is more sensitive to the variation of AC thickness than that of other layers due to the relative stress state changes in the upper (base) pavement layers.

#### *Influence of Base and Subbase CBR*

The influence of base and subbase strength on modulus was investigated for pavements with a 4-in. asphalt surface layer. CBR values of 60, 80, and 100 percent for the granular base and 20 and 40 percent for the granular subbase layers were used in the analysis. The results are shown in Figure 4.

In addition to the increase of the resilient modulus of the base course with the increase in subgrade CBR (discussed previously), the resilient modulus increases with the increase of the granular base and subbase CBR value, as expected. On the other hand, the increase of the base strength from 60 to 80 percent did not significantly increase the resilient modulus for either the subbase layer or the subgrade layers.

The resilient modulus for the first subgrade sublayer was found to be approximately  $1,000 \times \text{CBR}$ . In fact, after analyzing more than 300 FAA pavement structures, it has been verified that the range for resilient modulus is within  $800$  to  $1,200 \times \text{CBR}$  value of the subgrade. This factor is obviously close to the well-known  $1,500 \times \text{CBR}$  relationship developed by Shell researchers and is also consistent with coefficient multipliers of CBR for unbound granular material, which consider stress sensitivity.

#### **Pavement Life Studies**

##### *Influence of AC Thickness*

Several studies were likewise undertaken to investigate the influence of pavement layer variables on the predicted life

generated by PDAPD. As previously noted, the PDAPD program looks at fatigue fracture, subgrade deformation, and total pavement deformation of the system. Tables 2 and 3 present predicted life summaries indicating the relative influence of asphalt thickness and layer CBR values for subgrade, subbase, and base.

From the results presented in Table 2 it can be inferred that, for pavements designed according to FAA procedures, there is a relatively good agreement when predicting pavement life for pavements designed with 4-in. AC and 5 and 10 percent subgrade CBR. This finding is particularly true when the significant sensitivity of pavement variables to predicted repetitions to failure is considered.

If the CBR of the granular base is decreased to 60 percent instead of 100 percent and the AC thickness is increased by 1 in. (without any substitution of the other layer materials), the lives of the pavements still decrease by approximately 30 percent when designed for 5, 10, and 15 percent subgrade CBR. Comparisons made between pavements designed with 4 in. AC, 60 percent base CBR, and 20 percent subbase CBR (Table 2) and pavements designed with 5-in. AC (without any layer substitution), 60 percent base CBR, and 20 percent subbase CBR (Table 3) show that pavement life is always increased for the second case (5-in. AC). One example of these findings is shown in Figure 5.

These results definitely show that, for airfield pavements, it is possible to make design trade-offs among pavement layer thicknesses and qualities when base materials do not meet the standard specifications of minimum 80 percent CBR. These results also clearly explain the experience of Cardoso in the Brazilian Amazonian region, where lateritic base of 60 percent CBR has been used in some airfield pavements with good performance.

Another conclusion inferred from Table 2 is that the life (from a fatigue and total permanent deformation viewpoint) of pavements designed with an 8-in. AC surface layer decreases when the expected pavement life (according to the FAA procedure) increases. This result is accentuated for the

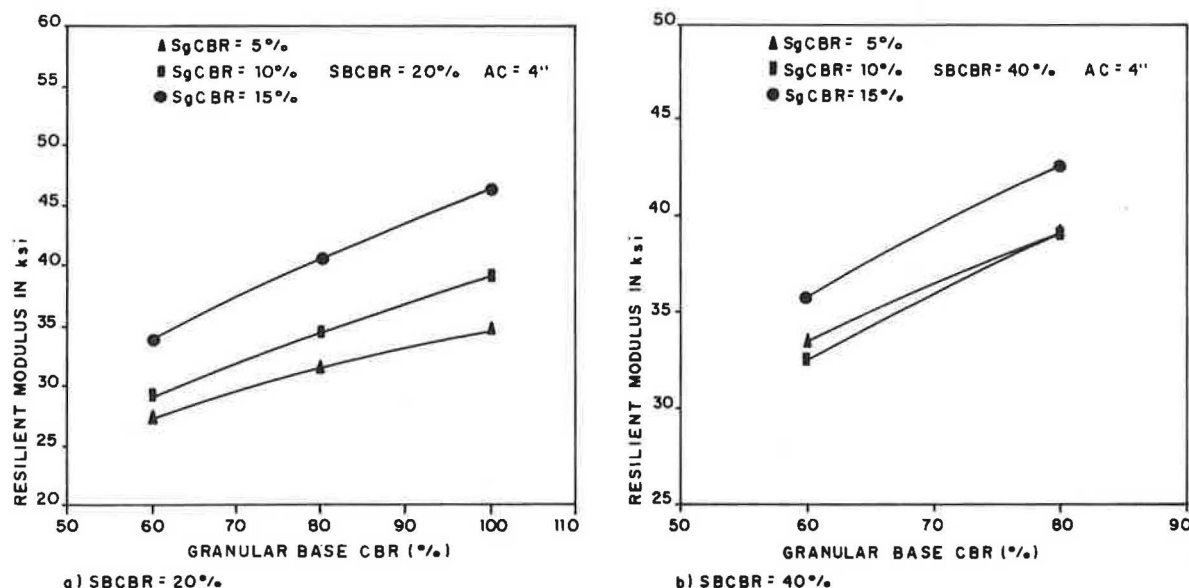


FIGURE 4 Effect of base and subbase CBR on base course resilient modulus.

TABLE 2 EFFECT OF AC THICKNESS ON PAVEMENT LIFE

Subgrade CBR (%)	Criterion	Traffic Repetitions (x 10,000)								
		AC = 4"*			AC = 5"***			AC = 8"*		
		P1	P2	P3	P1	P2	P3	P1	P2	P3
5	Fatigue	13.3	15.7	18.9	10.8	11.9	13.6	49.0	32.9	24.1
	Subgrade Def.	19.5	30.7	53.5	22.0	31.8	54.9	28.3	43.3	76.2
	Total Perm Def	5.6	(15.7)	(18.9)	2.8	6.3	(13.6)	(28.3)	21.3	7.7
10	Fatigue	19.6	21.0	24.5	14.3	15.4	16.4	26.2	26.9	27.3
	Subgrade Def.	21.0	25.9	36.7	26.2	32.5	45.5	36.7	49.3	70.6
	Total Perm Def	(19.6)	(21.0)	(24.5)	(14.3)	(15.4)	(16.4)	15.7	14.0	14.0
15	Fatigue	28.7	32.5	37.1	19.6	21.0	22.4	43.0	43.0	43.4
	Subgrade Def.	38.5	45.5	61.5	46.2	52.5	64.3	67.8	77.6	99.0
	Total Perm Def	(28.7)	(32.5)	(37.1)	(19.6)	(21.0)	(22.4)	(43.4)	29.7	25.5

- Notes:
1. Structures P1, P2, P3 are FAA designs for 60,000, 120,000, and 300,000 repetitions respectively.
  2. (\*) Granular Base CBR = 100%  
Granular Subbase CBR = 20%
  3. (\*\*\*) Granular Base CBR = 60%  
Granular Subbase CBR = 20%
  4. Numbers in parentheses ( ) are Traffic Repetitions greater than Value shown.

subgrade of 5 percent CBR and for the total permanent deformation criterion, as shown in Figure 6.

This finding can be explained by the increase of the subbase thickness done to compensate for the change in thickness of the AC layer. Besides the effect of the thicker subbase layer, the subbase material of 20 percent CBR also contributed to increasing the permanent deformation in that particular layer. In addition, for the 8-in. AC pavement the base course resilient moduli were affected by the variation in stress, as pointed out earlier. These results suggest that layer substitution ratios (and their subsequent use to determine equivalent structures) have to be analyzed carefully, considering all possible failure models. This finding is consistent with state-of-the-art knowledge of substitution ratios in highway and airfield design.

#### *Influence of Base and Subbase CBR Values*

The effect of the base and subbase CBR values on pavement life can be analyzed through the data presented in Table 3 and shown in Figures 7, 8, and 9, for the fatigue criterion, subgrade deformation criterion, and total plastic deformation criterion, respectively. The results indicate that the higher the base course or subbase CBR, the higher the pavement life in terms of any of the three criteria when the pavements are designed according to FAA procedure and the materials meet the required specifications.

Considering the fatigue and subgrade deformation criteria (Figures 7 and 8, respectively), the lower the subgrade CBR, the greater the benefit of a higher subbase CBR on the pavement life. On the other hand, the effect of higher subbase CBR on the pavement life in terms of the total plastic de-

formation criterion is not positive for pavements with 60 percent granular base CBR designed with 4-in. AC. As previously stated, the use of lower-quality materials for the base course must be viewed as a trade-off or balance among the pavement layer thicknesses, particularly with increases of the asphalt surface thickness.

#### **Layer Permanent Deformation**

##### *Influence of AC Thickness*

The contribution of each pavement material to permanent deformation is presented in Table 4. These values represent the average of the values obtained for pavements designed according to the FAA procedure for 60,000, 120,000, and 300,000 repetitions in a 20-year period. The mean value was used because there were no major differences among the three values for the various FAA pavement structures investigated.

From this table, it is clear that the higher the subgrade CBR, the greater the percentage contribution of the AC and subgrade layers to the total permanent deformation and the lower the contribution of the granular layers. Figure 9 shows that the plastic deformation is more distributed among the pavement materials when the subgrade CBR is increased from 5 to 15 percent.

Research studies conducted by Chou (9) on the effect of a stress factor on plastic deformation of subgrades are in agreement with these findings. Chou found that rutting of the subgrade was a function of the stress factor, defined as follows:

$$\text{Stress factor} = 28.5W^{0.5} \cdot \text{CBR}^{0.635} \quad (5)$$

TABLE 3 EFFECT OF BASE AND SUBBASE CBR ON PAVEMENT LIFE

Gran. Base CBR (%)	Subgrade CBR (%)	Criterion	Traffic Repetitions (x 10,000)					
			Subbase CBR = 20%			Subbase CBR = 40%		
			P1	P2	P3	P1	P2	P3
60	5	Fatigue	8.9	10.0	11.2	14.9	17.3	19.8
		Sq DF.	15.6	22.8	39.3	25.1	37.3	74.6
		T.P.D.	0.5	1.2	4.0	0.4	0.5	1.3
	10	Fatigue	12.0	12.7	13.9	15.8	16.9	18.5
		Sq DF.	17.5	21.7	30.4	21.0	26.2	36.7
		T.P.D.	3.4	4.2	7.0	1.3	1.4	1.3
	15	Fatigue	16.5	18.0	19.1	19.4	20.3	21.5
		Sq DF.	31.2	35.8	44.4	33.5	37.9	47.0
		T.P.D.	(16.5)	(18.0)	(19.1)	7.3	13.3	18.4
80	5	Fatigue	11.2	12.8	14.8	20.1	22.7	27.8
		Sq DF.	16.2	25.7	45.5	27.6	42.6	83.4
		T.P.D.	3.3	10.3	(14.8)	4.5	9.6	22.3
	10	Fatigue	15.8	19.1	17.0	21.3	23.1	26.0
		Sq DF.	19.6	34.6	23.9	23.9	29.8	42.2
		T.P.D.	15.7	(19.1)	(17.0)	15.0	18.9	(26.0)
	15	Fatigue	22.5	27.7	25.1	26.9	28.7	31.3
		Sq DF.	35.0	51.6	40.8	37.8	43.4	54.8
		T.P.D.	(22.5)	(27.7)	(25.1)	(26.9)	(28.7)	(31.3)
100	5	Fatigue	13.3	15.7	18.9	-	-	-
		Sq DF.	19.4	30.8	53.4	-	-	-
		T.P.D.	5.4	(15.7)	(18.9)	-	-	-
	10	Fatigue	19.3	21.0	24.3	-	-	-
		Sq DF.	21.0	25.9	36.4	-	-	-
		T.P.D.	(19.3)	(21.0)	(24.3)	-	-	-
	15	Fatigue	28.6	32.4	37.1	-	-	-
		Sq DF.	38.4	45.2	57.8	-	-	-
		T.P.D.	(28.6)	(32.4)	(37.1)	-	-	-

- Notes:
1. Structures P1, P2, P3 are FAA designs for 60,000, 120,000, and 300,000 repetitions respectively.
  2. Numbers in parentheses ( ) are Traffic Repetitions greater than Value shown.

where  $W$  is the equivalent single-wheel load and CBR is the subgrade strength.

On the basis of this equation, the higher the strength of the subgrade, the higher the stress factor and, consequently, the greater the percentage contribution of the subgrade to the total plastic deformation of the pavements.

The thicker the AC layer, the higher the permanent deformation for this layer and the lower the contribution of the granular layers. Table 4 shows that pavements designed for a subgrade of 5 percent CBR result in an increase of the plastic deformation contribution from 4 to 31 percent within the AC layer and a decrease from 92 to 65 percent for the granular layers when the AC thickness is increased from 4 to 8 in.

#### *Influence of Base and Subbase CBR Values*

Table 5 presents the contribution of each pavement layer material to total permanent deformation as a function of dif-

fering subgrade, subbase, and base strengths. The data indicate that increasing the subbase CBR (at the same base CBR) slightly increases the contribution of the granular layers to plastic deformation.

Once these pavement structures are designed according to the FAA procedure, the same discussion conducted for subgrades is applicable for subbase materials. In other words, the higher the subbase CBR, the higher the stress factor for that particular layer and the higher the percentage contribution of this layer to the total plastic deformation (9). The contribution of the granular layers to the plastic deformation decreases with an increase of the granular base CBR, whereas the AC and subgrade layer contributions simultaneously increase.

The results of the contribution of each pavement material to total permanent deformation agree with the literature (10-13).

After these preliminary results and verification of the PDAPD model, 3 years of analytical studies (more than 300 pavement

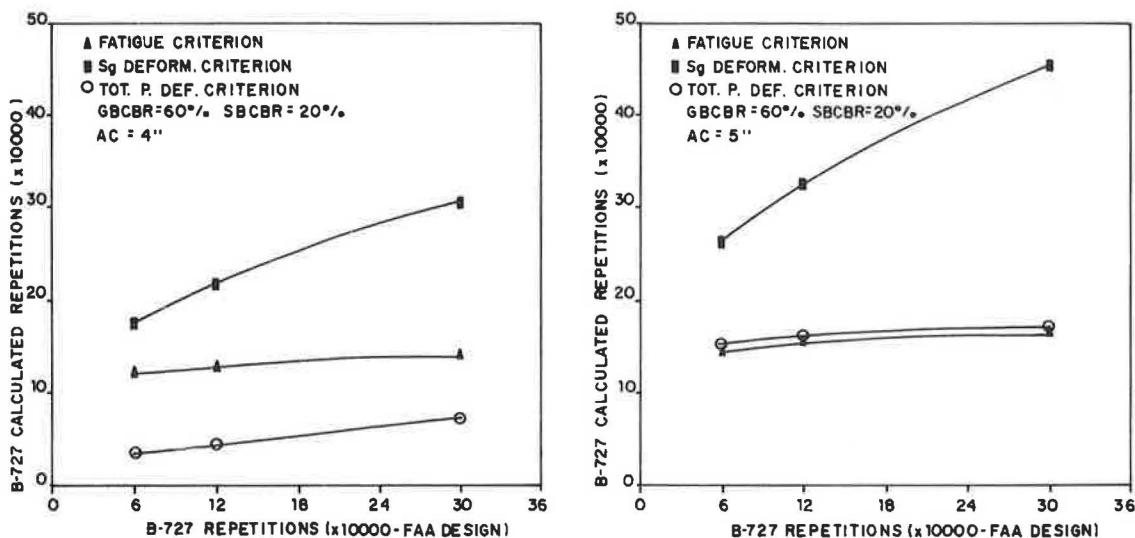


FIGURE 5 Effect of AC thickness on pavement life (subgrade CBR = 10 percent).

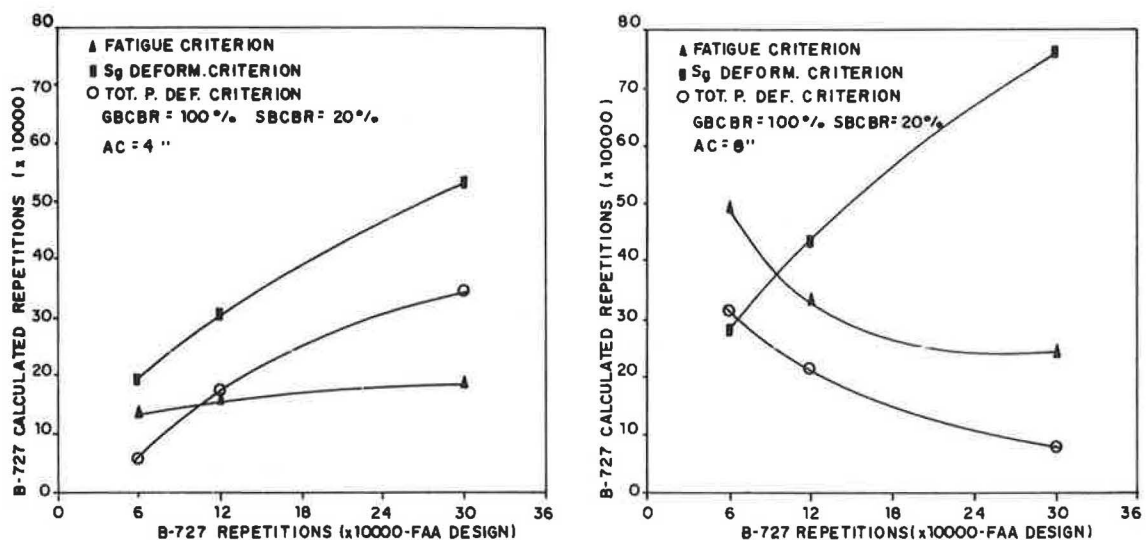


FIGURE 6 Effect of AC thickness on pavement life (design according to FAA procedure for 60,000 repetitions).

structures analyzed) and field studies (pavement evaluation and analysis of overlay design) were conducted. In general, these Brazilian studies reinforced the general findings, usefulness, and overall utility of the PDAPD model.

## CONCLUSIONS

The PDAPD model was developed to focus on the design and analysis of flexible airfield pavements using lateritic base and subbase gravels for Brazilian conditions. Following are some of the major capabilities of the model:

- The model calculates the dynamic modulus of AC layers on a monthly basis by considering environmental and asphalt mixture properties.

- The model calculates the resilient modulus for any layer of pavement having up to 10 layers, taking into consideration the nonlinearity of lateritic base, subbase, and subgrade materials, as well as the expected variation of their strength on a monthly basis.

- The model calculates the plastic information of each layer from the subgrade to the asphalt surface and accumulates the total permanent deformation for the pavement structure on a monthly basis. The permanent deformation of the asphalt layers is modeled with the use of the elastic deformation within the layers caused by a particular aircraft type. The plastic deformations of the lateritic base, subbase, and subgrade layers are calculated through statistical models developed in this study on the basis of dynamic (repeated) load permanent deformation laboratory results. These models incorporate the



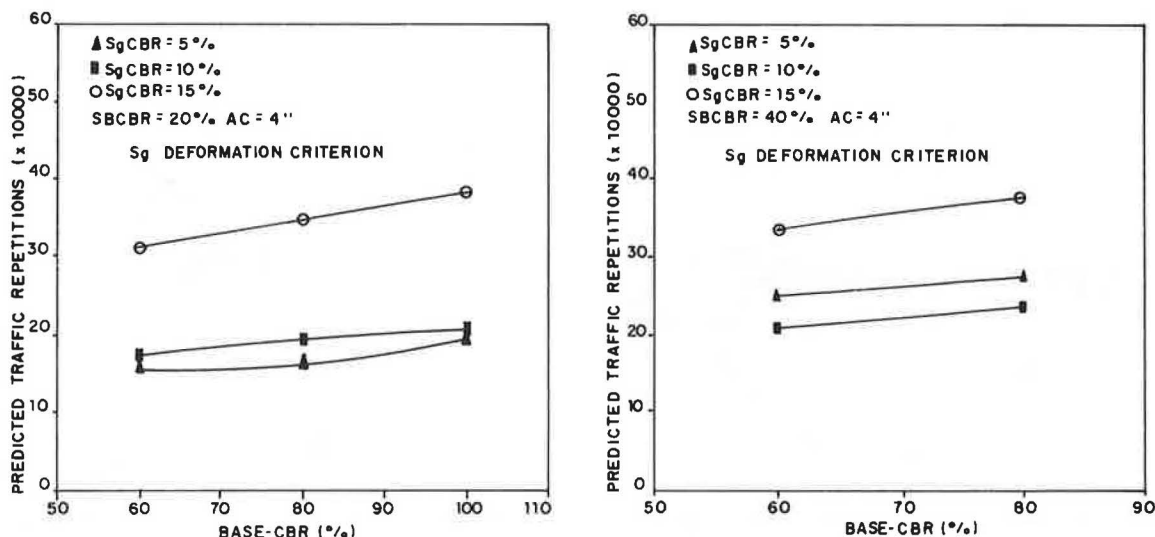


FIGURE 7 Effect of subbase and base CBR on pavement life (subgrade deformation criterion).

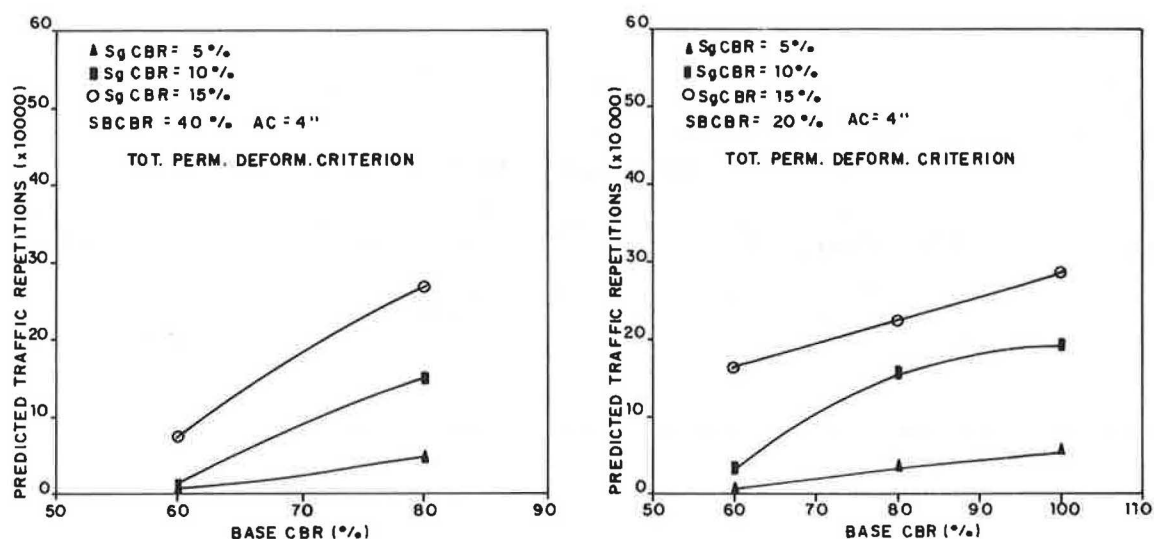


FIGURE 8 Effect of subbase and base CBR on pavement life (total permanent deformation criterion).

material strength by CBR and the state of stress at the middle of the depth of each layer.

- The computer program can be used to analyze airfield flexible pavements, taking into consideration all aspects presented in the PDAPD model. Three basic criteria are used: (a) tensile strain at the bottom of the AC layers (fatigue), (b) compressive strain at the top of the subgrade (subgrade deformation), and (c) total permanent deformation.

A preliminary verification study of the PDAPD model was done by analyzing 65 cases of pavement structures designed according to the FAA procedure for three levels of load applications. Following are the main conclusions of that study:

- The resilient modulus of the lateritic granular base increases with an increase of the CBR strengths of the subgrade,

subbase, and base course. The granular base modulus is more sensitive to thicker AC layers than to changes in either the subbase or subgrade CBR.

- For over 300 pavement structures studied to date, the resilient modulus of the first subgrade layer was found to be around  $1,000 \times \text{CBR}$  (range of  $800$  to  $1,200 \times \text{CBR}$ ).

- For pavement life, the fatigue criterion was more critical than the subgrade deformation criterion on all pavement structures studied for the B-727-100 aircraft. For pavements designed with a 4-in. asphalt layer, the total plastic deformation criterion was less critical than the subgrade deformation criterion. This same trend was not found for pavements designed with an 8-in.-thick asphalt layer, which suggests that the substitution of layer materials must be cautiously conducted.

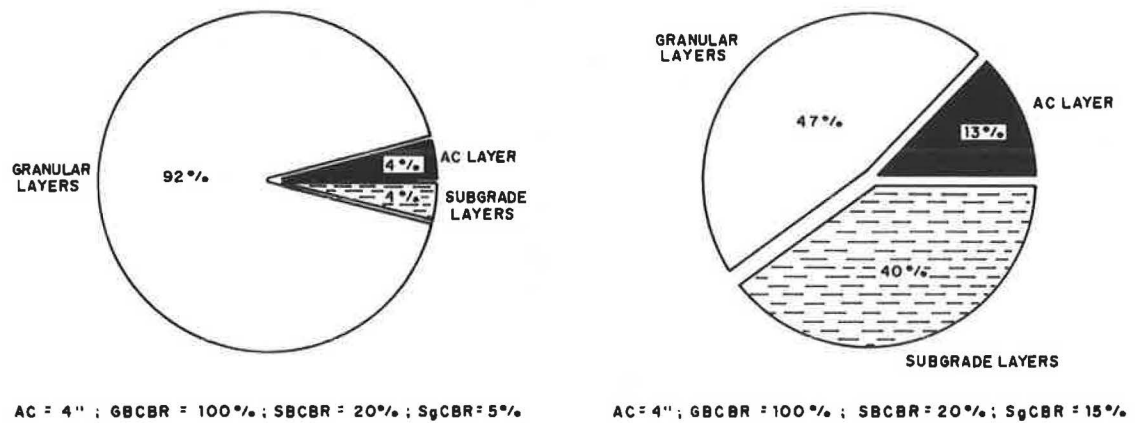


FIGURE 9 Contribution of plastic deformation from each type of material.

TABLE 4 EFFECT OF AC THICKNESS ON LAYER CONTRIBUTION PERCENTAGE OF TOTAL PERMANENT DEFORMATION

Subgrade CBR (%)	Percent of Total Permanent Deformation (%)								
	AC = 4"			AC = 5"			AC = 8"		
	AC	Gran	Sq	AC	Gran	Sq	AC	Gran	Sq
5	4.0	92.0	4.0	4.0	93.0	3.0	31.0	65.0	4.0
10	6.0	76.0	18.0	7.0	81.0	12.0	55.0	34.0	11.0
15	13.0	47.0	40.0	11.0	66.0	23.0	67.0	17.0	16.0

TABLE 5 EFFECT OF BASE AND SUBBASE CBR ON LAYER CONTRIBUTION PERCENTAGE OF TOTAL PERMANENT DEFORMATION

Granular Base CBR (%)	Subgrade CBR (%)	Percent of Total Permanent Deformation (%)					
		Subbase CBR = 20%			Subbase CBR = 40%		
		AC	Gran	Sq	AC	Gran	Sq
60	5	2.0	96.0	2.0	1.0	97.0	2.0
	10	4.0	85.0	11.0	3.0	89.0	8.0
	15	7.0	71.0	22.0	6.0	76.0	18.0
80	5	3.0	94.0	3.0	3.0	95.0	2.0
	10	6.0	78.0	16.0	5.0	83.0	12.0
	15	11.0	54.0	35.0	9.0	65.0	26.0
100	5	4.0	92.0	4.0	-	-	-
	10	6.0	76.0	18.0	-	-	-
	15	13.0	47.0	40.0	-	-	-

• If the same conditions (required by the FAA procedure) are kept constant but a 60 percent material is used for the base instead of 100 percent and the asphalt layer thickness is increased by only 1 in., similar performance (life) is obtained for pavements designed for the three levels of load applications studied. The findings strongly suggest that in designing airfield pavements it is possible to make a trade-off among the pavement layer thicknesses and material quality when the materials do not meet the CBR standard specifications.

• For pavements designed with 4 in. of asphalt surfacing, the higher the base or subbase CBR, the longer the pavement life for all three failure criteria.

• The higher the subgrade CBR, the more distributed the plastic deformation percentage among the pavement materials (AC, base and subbase, and subgrade layers). The thicker the AC layer, the larger the plastic deformation for this layer. In addition, the contribution of the granular layers for the total permanent deformation becomes smaller.

These results provide an example of the flexibility and ability of the PDAPD model for designing and analyzing flexible airfield pavements. In particular, PDAPD has significant potential when materials do not meet the standard requirements and specifications currently in use.

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