DESIGN OF PRESTRESSED CONCRETE AIRFIELD PAVEMENTS UNDER DUAL AND DUAL TANDEM WHEEL LOADING

Dual and dual tandem wheel loading for aircraft can be converted to equivalent single wheel loads and the design method previously devised for prestressed concrete pavements can be applied to heavier aircraft loadings. Design charts are presented and examples for their use are given.

Michel Sargious
Dept. of Civil Engineering
The University of Calgary
Calgary, Alberta, Canada

S. K. Wang
Dept. of Civil Engineering
The University of Calgary
Calgary, Alberta, Canada

Trends toward heavier and heavier aircraft have emphasized the need for multiple wheel landing gears, where a large load can be distributed over several wheels. As a convenient means for design of pavements under such loads, these multiple wheel gear loads are converted to equivalent single wheel loads which give the same maximum stress in the pavement[4]. Once the equivalent single wheel loads are determined, the design can proceed in the same manner used for pavement slabs subjected to a single wheel load. This offers a convenient means for both the design and evaluation of airfield pavements subjected to loading applied through various types of multiple wheel undercarriages.

After the values of the single load that represent the loads of various dual and dual tandem wheel undercarriages are determined, the stresses are calculated for different cases of prestressed concrete slabs resting on subgrades having variable strength.

Constant standard values are allocated to the spacings between the wheels. The main variables are: the value of the load, the tire pressure, the modulus of subgrade reaction, the coefficient of subgrade friction, the modulus of rupture of the concrete, and the length and thickness of the slab.

Five charts are plotted for the case of dual wheel undercarriages and two charts are plotted for the case of dual tandem wheel undercarriages. These charts can be easily used by design engineers to determine the thickness, and the corresponding required prestress, for prestressed concrete airfield pavement slabs. It also allows the choice between different possible alternatives in trying to achieve optimal solutions.

In a previous paper[3], the authors presented charts for the design of prestressed concrete pavement slabs subjected to single wheel loads. In that paper they showed the considerable improvement in concrete pavement design that can be achieved by prestressing, the basic concepts for design, as well as the different prestressing techniques that can be used in such pavements. Also, a cost formula was developed that can be used in choosing an economic alternative for the prestressed concrete pavement.

BASIC DESIGN CONCEPTS

The analysis used in determining the equivalent single wheel load is based on a theory developed by Westergaard[2]. It consists of determining the magnitude and contact area of a single wheel load which, when placed centrally on a concrete slab, will produce the same maximum stress as that produced by two or four closely spaced loads representing the dual or dual tandem load of an aircraft undercarriage.

The pavement variables are included in one value

$$l = \sqrt[4]{\frac{E_c h^3}{12(1-\nu^2)k}}$$

where l = radius of relative stiffness

E_c = modulus of elasticity of the concrete

h = thickness of the concrete slab

k = modulus of subgrade reaction

ν = Poisson's ratio for concrete

The ratio of the total gear load to an equivalent single wheel load can then be obtained from charts drawn for this purpose[4]. The approximate dimensions of the equivalent single wheel contact area can be obtained, using the same value of the tire pressure underneath the wheels.

The stresses due to aircraft loads can then be determined using Westergaard's formula for an interior load acting on elliptical area[2,3]. The adoption of the center loading condition is considered valid for airport pavements inasmuch as aircraft rarely travel near the outside edge of the pavement. In addition, in prestressed pavements, there is enough load transfer at the interior longitudinal joints due to transverse prestressing. The stresses due to load, when added to the curling stresses and the stresses due to subgrade friction, should not give values higher than $f_t + f_p$, where

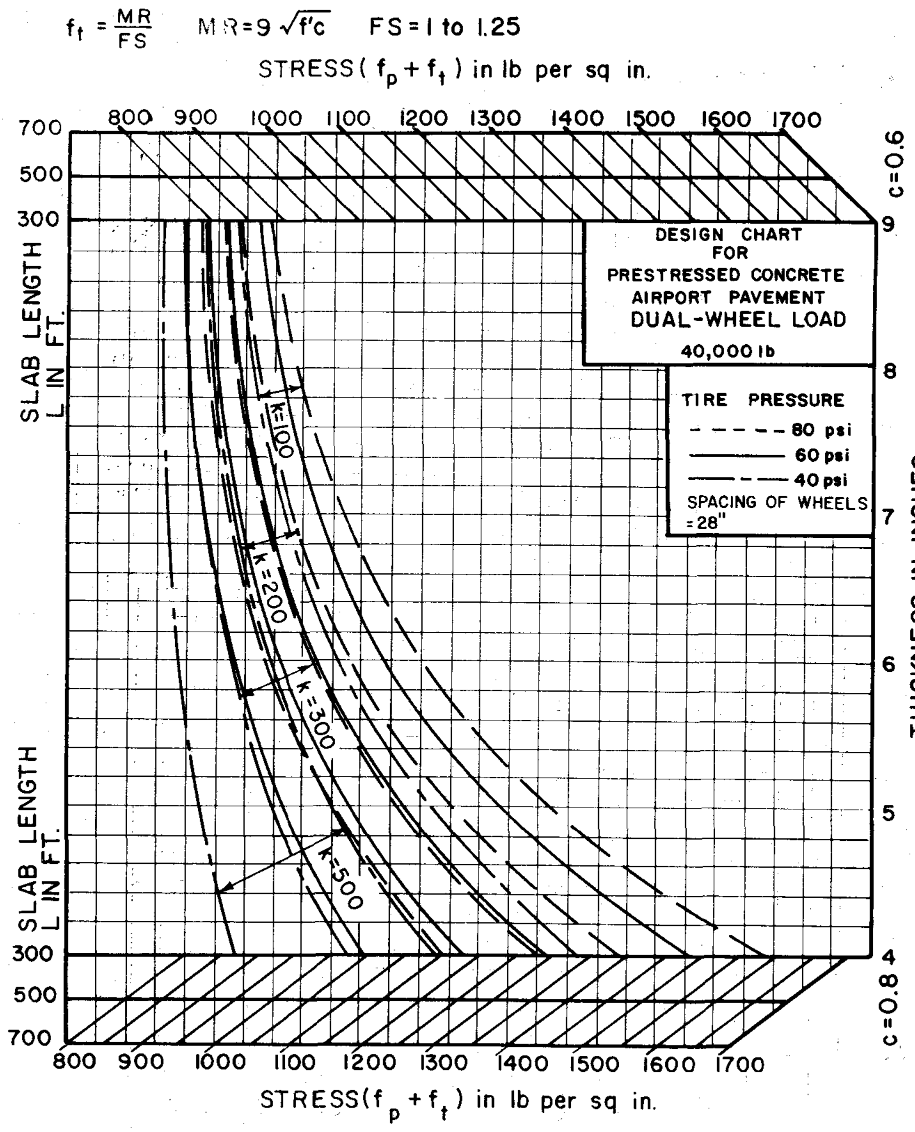
f_t = allowable concrete flexural stress $= \dfrac{\text{modulus of rupture}}{\text{factor of safety}}$

f_p = compressive stress in concrete due to prestressing

The formulae used in calculating the curling stresses and the stresses due to subgrade friction are given in References 1 and 3 and will not be repeated here.

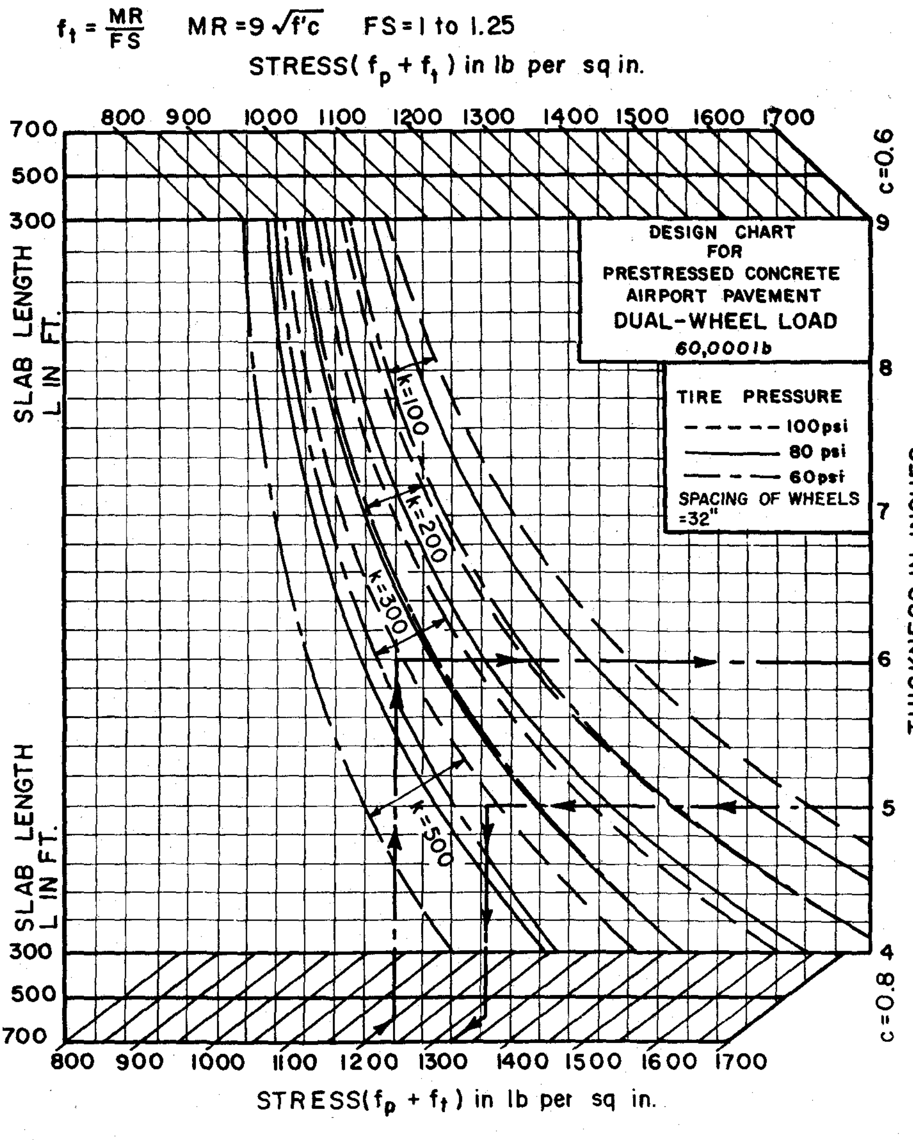
PREPARATION OF THE DESIGN CHARTS

A computer program is set to calculate the values of the equivalent single wheel load. Another program is prepared to give the values of the stresses due to load, the curling stresses and the stresses due to friction.



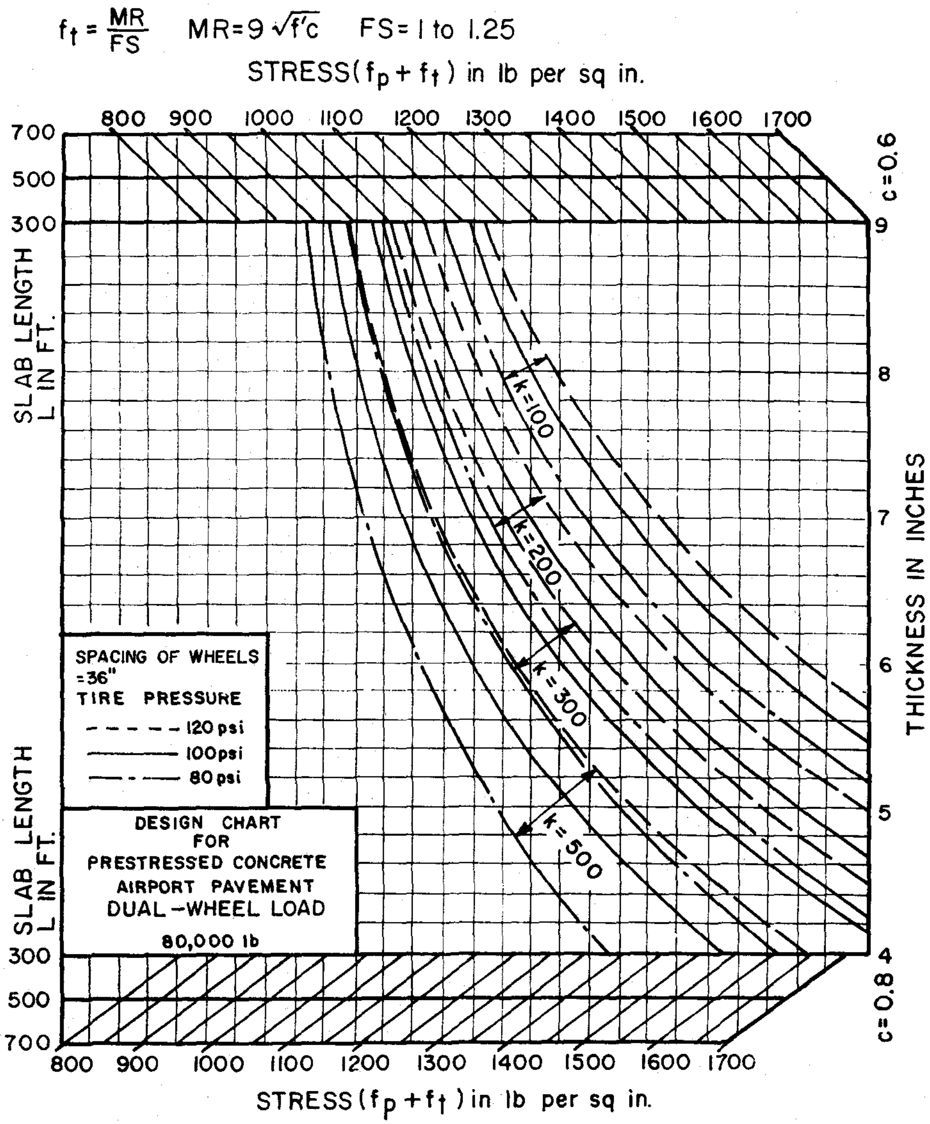
$f_t = \frac{MR}{FS}$ MR=9 $\sqrt{f'c}$ FS=1 to 1.25
STRESS($f_p + f_t$) in lb per sq in.
800 900 1000 1100 1200 1300 1400 1500 1600 1700
700
500
300
SLAB LENGTH L IN FT.
c=0.6
9
8
7
6
5
4
c=0.8
THICKNESS IN INCHES
DESIGN CHART FOR PRESTRESSED CONCRETE AIRPORT PAVEMENT
DUAL-WHEEL LOAD
40,000 lb
TIRE PRESSURE
80 psi
60 psi
40 psi
SPACING OF WHEELS =28"
k=100
k=200
k=300
k=500
SLAB LENGTH L IN FT.
300
500
700
800 900 1000 1100 1200 1300 1400 1500 1600 1700
STRESS($f_p + f_t$) in lb per sq in.

Fig. 1



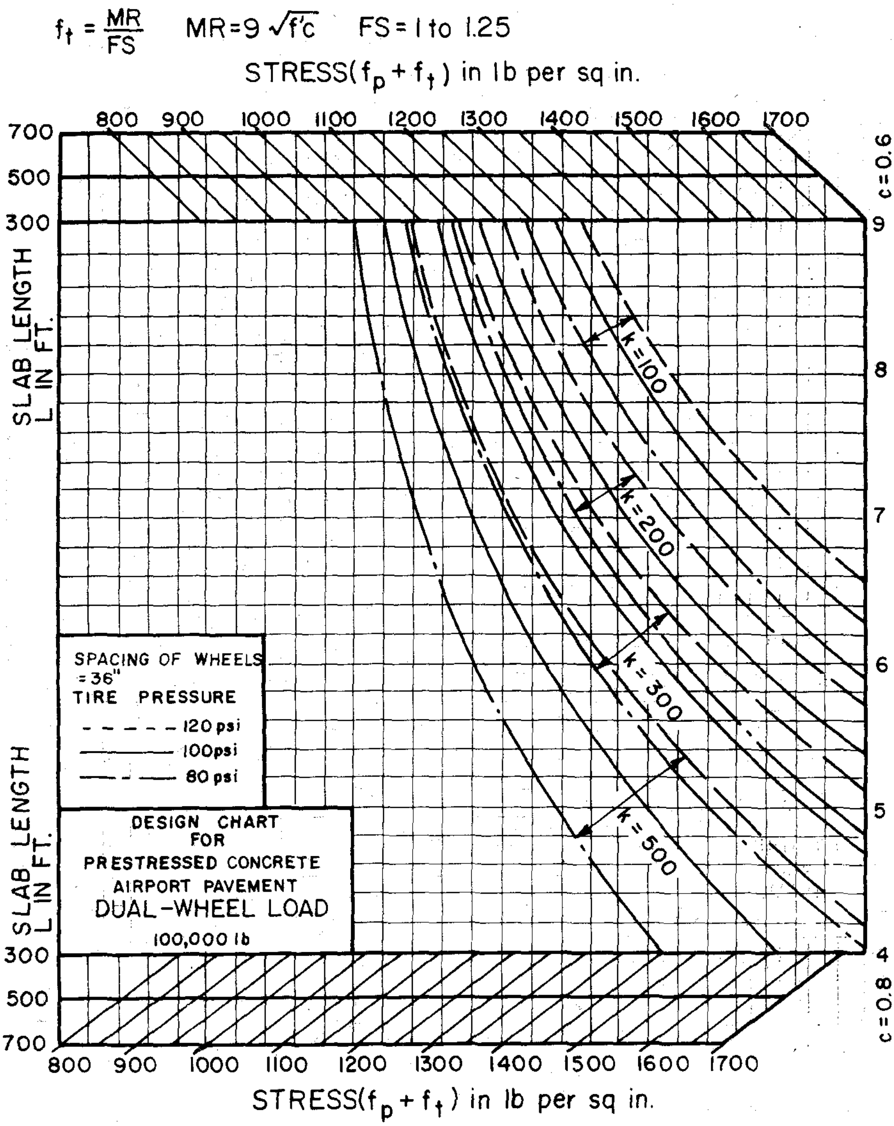
$f_t = \frac{MR}{FS}$ MR = 9 $\sqrt{f'c}$ FS = 1 to 1.25
STRESS($f_p + f_t$) in lb per sq in.
800 900 1000 1100 1200 1300 1400 1500 1600 1700
700
500
300
SLAB LENGTH L IN FT.
c=0.6
9
8
7
6
5
4
c=0.8
THICKNESS IN INCHES
DESIGN CHART FOR PRESTRESSED CONCRETE AIRPORT PAVEMENT
DUAL-WHEEL LOAD
60,000 lb
TIRE PRESSURE
100 psi
80 psi
60 psi
SPACING OF WHEELS =32"
k=100
k=200
k=300
k=500
300
500
700
SLAB LENGTH L IN FT.
800 900 1000 1100 1200 1300 1400 1500 1600 1700
STRESS($f_p + f_t$) in lb per sq in.

Fig. 2



$f_t = \frac{MR}{FS}$ $MR = 9\sqrt{f'c}$ FS = 1 to 1.25
STRESS ($f_p + f_t$) in lb per sq in.
800 900 1000 1100 1200 1300 1400 1500 1600 1700
700
500
300
SLAB LENGTH L IN FT.
c = 0.6
9
8
7
6
5
4
THICKNESS IN INCHES
k=100
k=200
k=300
k=500
SPACING OF WHEELS = 36"
TIRE PRESSURE
120 psi
100 psi
80 psi
DESIGN CHART FOR PRESTRESSED CONCRETE AIRPORT PAVEMENT
DUAL-WHEEL LOAD
80,000 lb
SLAB LENGTH L IN FT.
300
500
700
c = 0.8
800 900 1000 1100 1200 1300 1400 1500 1600 1700
STRESS ($f_p + f_t$) in lb per sq in.

Fig. 3



$f_t = \frac{MR}{FS}$ MR=9 $\sqrt{f'c}$ FS = 1 to 1.25
STRESS($f_p + f_t$) in lb per sq in.
800 900 1000 1100 1200 1300 1400 1500 1600 1700
700
500
300
SLAB LENGTH L IN FT.
c=0.6
9
8
7
6
5
4
c=0.8
THICKNESS IN INCHES
k=100
k=200
k=300
k=500
SPACING OF WHEELS =36"
TIRE PRESSURE
120 psi
100psi
80 psi
DESIGN CHART FOR PRESTRESSED CONCRETE AIRPORT PAVEMENT
DUAL-WHEEL LOAD
100,000 lb
SLAB LENGTH L IN FT.
300
500
700
800 900 1000 1100 1200 1300 1400 1500 1600 1700
STRESS($f_p + f_t$) in lb per sq in.

Fig. 4

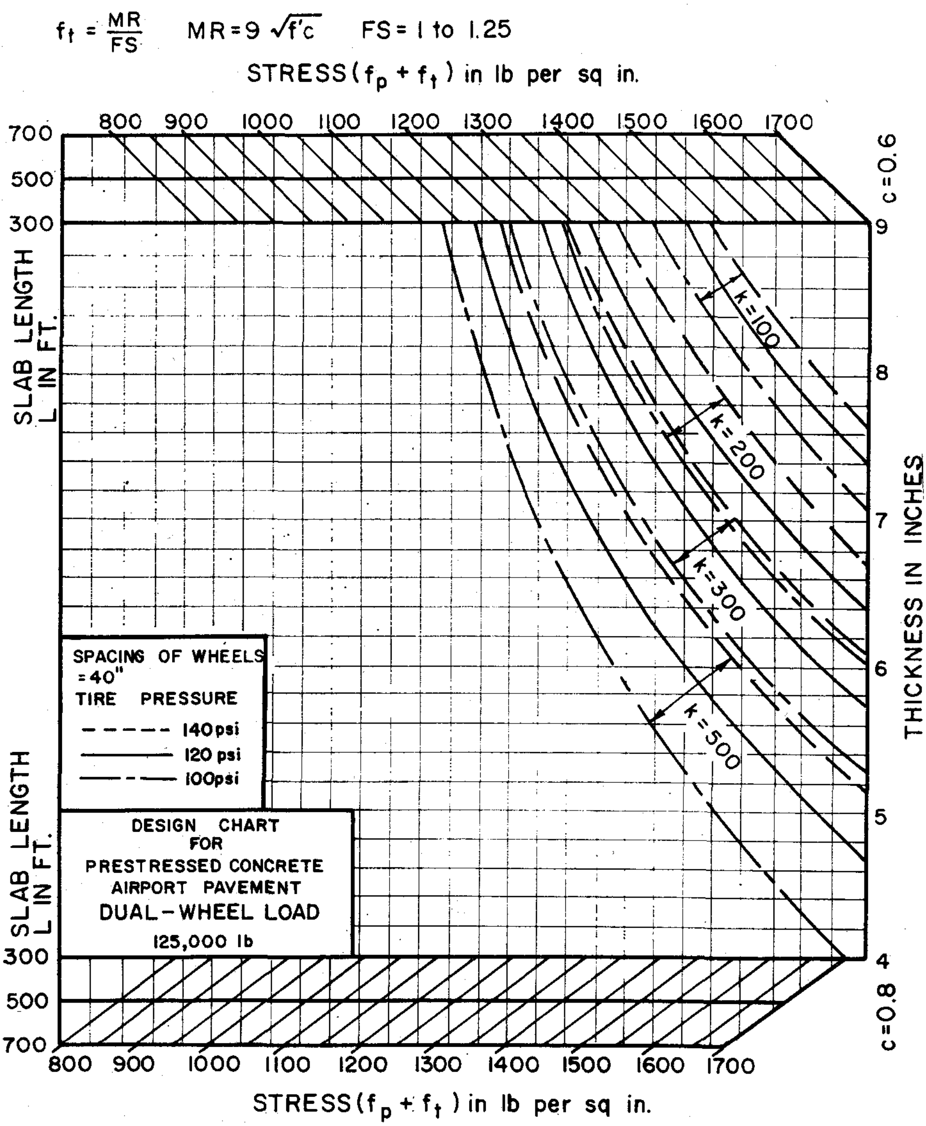
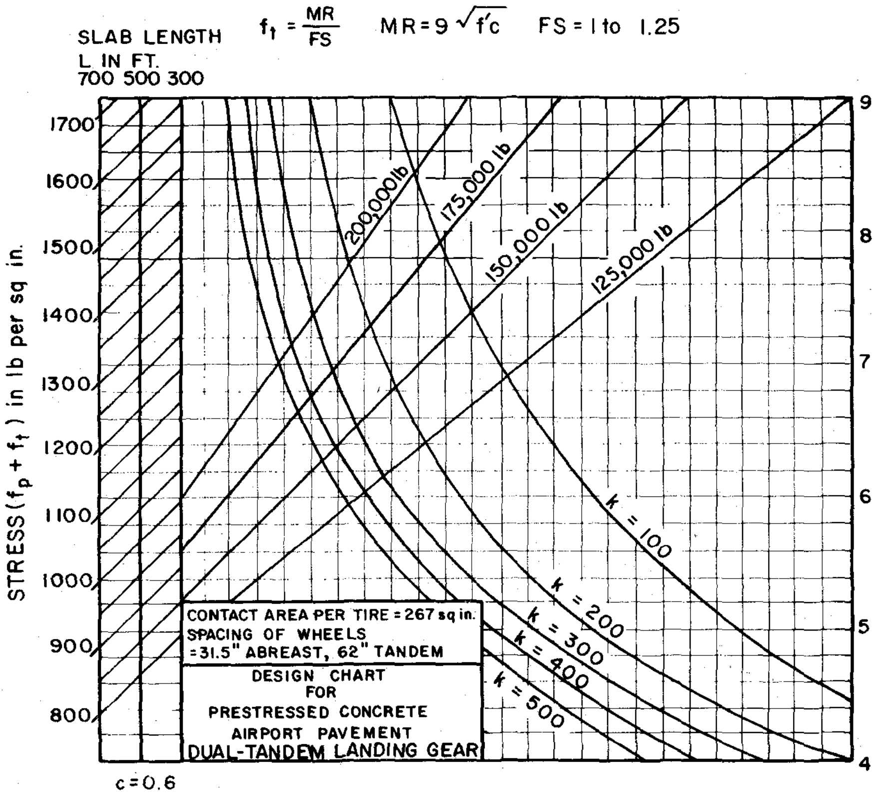

$f_t = \frac{MR}{FS}$ $MR = 9\sqrt{f'c}$ FS = 1 to 1.25
STRESS ($f_p + f_t$) in lb per sq in.
800 900 1000 1100 1200 1300 1400 1500 1600 1700
700
500
300
SLAB LENGTH L IN FT.
c=0.6
9
8
7
6
5
4
c=0.8
THICKNESS IN INCHES
k=100
k=200
k=300
k=500
SPACING OF WHEELS =40"
TIRE PRESSURE
140psi
120 psi
100psi
DESIGN CHART
FOR
PRESTRESSED CONCRETE
AIRPORT PAVEMENT
DUAL-WHEEL LOAD
125,000 lb
SLAB LENGTH L IN FT.
300
500
700
800 900 1000 1100 1200 1300 1400 1500 1600 1700
STRESS ($f_p + f_t$) in lb per sq in.

Fig. 5



SLAB LENGTH
L IN FT.
700 500 300
$f_t = \frac{MR}{FS}$
$MR = 9\sqrt{f'c}$
FS = 1 to 1.25
1700
1600
1500
1400
1300
1200
1100
1000
900
800
STRESS ($f_p + f_t$) in lb per sq in.
9
8
7
6
5
4
THICKNESS IN INCHES
200,000 lb
175,000 lb
150,000 lb
125,000 lb
k = 100
k = 200
k = 300
k = 400
k = 500
CONTACT AREA PER TIRE = 267 sq in.
SPACING OF WHEELS
= 31.5" ABREAST, 62" TANDEM
DESIGN CHART
FOR
PRESTRESSED CONCRETE
AIRPORT PAVEMENT
DUAL-TANDEM LANDING GEAR
c = 0.6

Fig. 6

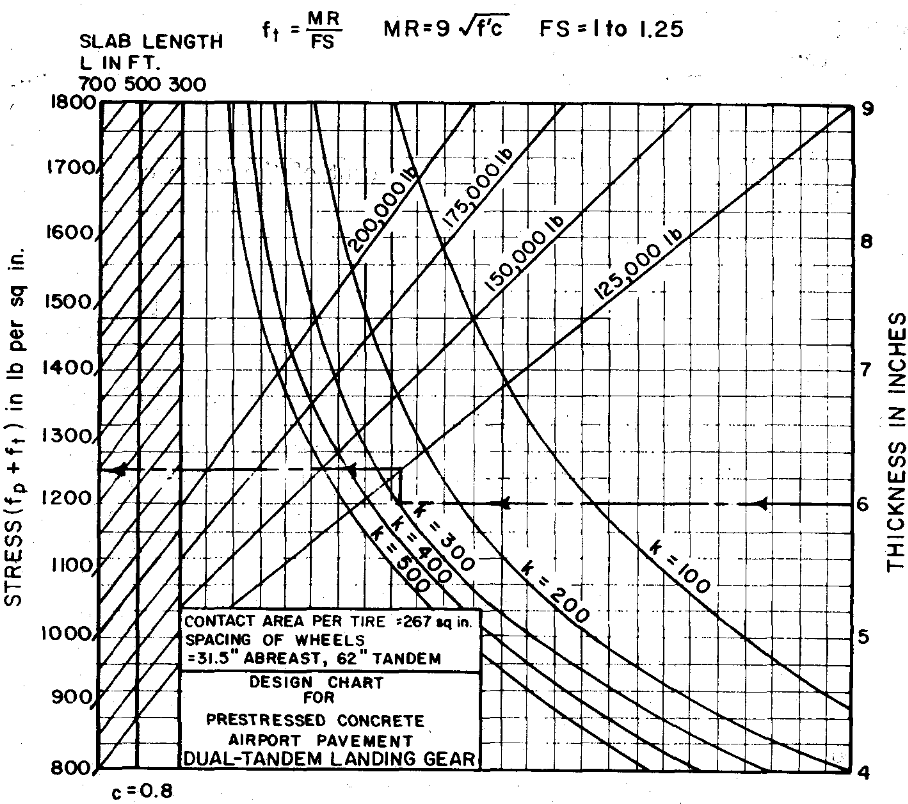

$f_t = \frac{MR}{FS}$ MR=9 $\sqrt{f'c}$ FS = 1 to 1.25
SLAB LENGTH
L IN FT.
700 500 300
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
STRESS ($f_p + f_t$) in lb per sq in.
c = 0.8
9
8
7
6
5
4
THICKNESS IN INCHES
200,000 lb
175,000 lb
150,000 lb
125,000 lb
k = 100
k = 200
k = 300
k = 400
k = 500
CONTACT AREA PER TIRE = 267 sq in.
SPACING OF WHEELS
= 31.5" ABREAST, 62" TANDEM
DESIGN CHART
FOR
PRESTRESSED CONCRETE
AIRPORT PAVEMENT
DUAL-TANDEM LANDING GEAR

Fig. 7

For determining the frictional stresses, slab lengths L between 300 ft. and 700 ft. (90 to 210 m) together with two arbitrarily chosen values for the coefficient of subgrade friction ($c = 0.60$ and $c = 0.80$) are considered. Although the charts are plotted for these values, the same charts can also be used for slab lengths or for coefficients of friction outside the above mentioned ranges(3).

To obtain practical results, the following points are considered in making this study and in preparing the charts:

1. The pavement slab thickness can be between 4 and 9 in. (10 and 23 cm).
2. The modulus of subgrade reaction can have any value between 100 and 500 lb./in.^{3} (2800 to 14,000 t/m^3).
3. The sum of the allowable concrete flexural stress plus the concrete stress due to prestressing can be any value between 800 and 1700 psi (56 to 120 kg/cm^2).
4. The concrete used is assumed to have a quality of 4000 to 6000 psi (281 to 422 kg/cm^2).
5. The compressive stress in the concrete due to prestressing should not exceed 800 psi (56 kg/cm^2) to avoid excessive compressive stresses at the top surface of the pavement slab. At the same time this stress should not be less than the frictional stress plus 150 psi (10 kg/cm^2) to avoid the development of transverse cracks in the central part of the pavement slab.
6. The allowable concrete flexural stress f_t can be allocated a value between 80 and 100 percent the modulus of rupture of the concrete.
7. The allowable stress in the prestressing steel f_{se} should not exceed, after losses, 60 percent of the specified minimum ultimate tensile strength of the prestressing steel.
8. A transverse prestressing of 60 percent of the value of longitudinal prestressing for slabs 700 ft. (210 m) long and of 70 percent of the value of longitudinal prestressing for slabs 300 ft. (90 m) long may be used.

Charts for dual wheel landing gear. A separate chart (Figs. 1 to 5) is prepared for each of the five loads considered ($P = 40$, 60, 80, 100 and 125 kips) (18.2, 27.2, 36.3, 45.4 and 56.7 t). The load indicated on each chart represents the actual maximum load on one dual wheel landing gear.

Together with each load, three different values are considered for the tire pressure.

Charts for dual tandem wheel landing gear. Two charts (Figs. 6 and 7) are prepared for this case. In the first chart a coefficient of subgrade friction $c = 0.60$ is considered while the second chart is plotted for $c = 0.80$. Both charts are for an actual maximum load on one dual tandem wheel landing gear ranging between 125 and 200 kips (56.7 to 90.8 t).

Only one value for the contact area per tire is considered and is taken equal to 267 in.^{2} (1720 cm^2).

USE OF DESIGN CHARTS

Once the load on the landing gear, the tire pressure and the modulus of subgrade reaction are given, a preliminary reasonable value for the thickness can be assumed. The corresponding value for $f_t + f_p$ can be determined from the charts. If the value of f_t is estimated, according to the quality of the concrete used and according to the chosen value for the factor of safety, then the required value for the prestressing stress f_p can be determined. Should another value for f_p be preferred, then the thickness required to correspond to the new value of $f_t + f_p$ can be easily obtained.

Sample design problem for aircraft with dual wheel landing gears.

Given: P (on one landing gear assembly) = 60 kips (27.2 t)
tire pressure = 80 psi (5.6 kg/cm²)
f'_c = 4500 psi (316 kg/cm²)
k = 400 pci (11,000 t/m³)
c = 0.8
L = 600 ft. (180 m)
spacing of wheels = 32 in. (81 cm)

Required: The thickness of prestressed concrete pavement slab and the prestress in the concrete.

Solution:
Modulus of rupture of concrete = $9\sqrt{f'_c}$ = 600 psi (42 kg/cm²)
Assuming a factor of safety equal to 1.2, then

$$f_t = \frac{\text{MR}}{\text{FS}} = \frac{600}{1.2} = 500 \text{ psi } (35 \text{ kg/cm}^2)$$

Assume a slab thickness of 5 in. (12.7 cm) and enter the design chart in Fig. 2 on the right margin at that thickness. Proceed left horizontally to the curve for $k = 400$ pci and tire pressure = 80 psi (interpolate between the two full curves for $k = 300$ pci and $k = 500$ pci).

Since $c = 0.8$, proceed vertically downward, to meet the horizontal line representing $L = 600$ ft. and then parallel to the inclined lines (as shown by the arrowed line in Fig. 2) to the lower edge of the chart. This gives a value of 1320 psi (93 kg/cm²) for $f_t + f_p$.

The prestressing stress required in the concrete for this case is:

$$f_p = 1320 - 500$$
$$= 820 \text{ psi } (58 \text{ kg/cm}^2)$$
$$> 800 \text{ psi } (56 \text{ kg/cm}^2)$$

Should a prestressing stress of say 700 psi (49 kg/cm²) be recommended, then the required new slab thickness can be determined as follows:

Enter the design chart in Fig. 2 on the bottom margin at the new value $f_t + f_p = 500 + 700 = 1200$ psi (85 kg/cm²) and proceed parallel to the inclined lines to meet the horizontal line corresponding to $L = 600$ ft.

Proceed upward vertically to meet the curve for $k = 400$ pci and tire pressure 80 psi and then horizontally to the right. The required new thickness can be read on the right edge of the chart which is 6 in. (15.2 cm) in this example.

Sample design problem for aircraft with dual tandem wheel landing gears.

Given: P (on one landing gear assembly) = 125 kips (56.7 t)
f'_c = 5500 psi (386 kg/cm²)
c = 0.8
k = 300 pci (8250 t/m³)
L = 700 ft. (210 m)
contact area per tire
= 267 sq. in. (1674 cm²)
spacing of wheels
= 31.5 in. (80 cm) abreast
= 62 in. (158 cm) tandem

Required: The thickness of prestressed concrete pavement slab and the prestress in the concrete.

Solution:

Modulus of rupture of concrete = $9\sqrt{f'_c}$ = 670 psi (47 kg/cm²)
Assuming a factor of safety equal to 1.1, then

$$f_t = \frac{MR}{FS} = \frac{670}{1.1} \cong 600 \text{ psi}$$

Assume a slab thickness of 6 in. (15.2 cm) and enter the design chart in Fig. 7 on the right margin at that thickness. Proceed left horizontally to the curve for $k = 300$ pci. Proceed vertically to meet the inclined line for $P = 125{,}000$ lb. and horizontally to the left to meet the vertical line representing $L = 700$ ft. (as shown by the arrowed line in Fig. 7). The value of $f_t + f_p$ can be read on the left margin of the chart and is equal to 1250 psi (88 kg/cm²).

The required compressive stress in the concrete due to prestressing is

$$f_p = 1250 - 600$$
$$= 650 \text{ psi } (46 \text{ kg/cm}^2)$$

CONCLUSIONS

In recent years, aircraft volumes and weights are increasing tremendously. This puts new responsibilities on civil engineers to make continued improvement and up-dating of pavement design and construction.

A considerable improvement in concrete pavement design can be achieved by prestressing. The precompression in the concrete due to prestressing is cumulative with the inherent flexural strength of the material to produce an increase in stress range in the flexural zone. This results in several advantages such as absence of cracks in road surface, large decrease in the number of transverse joints thus giving a smooth and comfortable travelling surface, and a big reduction in slab thickness thus achieving economy in cost.

Prestressed concrete pavements offer two distinct design advantages, especially when designed to receive aircraft with multiple wheel landing gears. The first advantage is that they are subjected to smaller curling stresses due to temperature since the curling stresses are directly proportional to slab thickness. The second advantage is that slabs with smaller thickness give smaller values for the equivalent single wheel load, which is used in the design to replace the load on multiple wheel undercarriages.

Because of these facts, design charts are developed to determine the pavement thickness and prestress required for concrete airfield pavements once the load, tire pressure, modulus of subgrade reaction and coefficient of subgrade friction are given. These charts also allow the use of a cost function[3] and the choice of different alternatives from which an economic solution can be determined.

REFERENCES

1. Leonhardt, F., "Prestressed Concrete Design and Construction", 2nd Edition, Wilhelm Ernst and Sohn, Berlin, 1964, pp. 554-568.
2. Westergaard, H. M., "New Formulas for Stresses in Concrete Pavements of Airfields", ASCE *Proceedings*, May 1947, pp. 425-439.
3. Sargious, Michel and Wang, S. K., "Economical Design of Prestressed Concrete Pavements", *PCI Journal*, July-August 1971, pp. 64-79.
4. "Airport Paving", Federal Aviation Agency, U.S.A., November 1962, pp. 32-40.
5. Sargious, M. and Bissada, A., "Strengthening Prestressed Concrete Pavement", *ACI Journal*, November 1969, pp. 920-925.

Discussion of this paper is invited. Please forward your comments to PCI Headquarters by March 1 to permit publication in March-April 1972 issue of the PCI JOURNAL.