# Combined Effect of Traffic Loads and Thermal Gradients on Concrete Pavement Design 

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#### Abstract

The purpose of this work is to study the behavior of concrete pavements under the simultaneous action of traffic and thermal gradients in concrete slabs. A new procedure for the structural design of concrete pavements in Spain is presented. A fatigue equation, taken from an adjustment of Tepfer's fatigue law and based on data on the behavior of several concrete pavements in Spain, is proposed. Analyses of loading stresses, thermal warping stresses, and simultaneous action stresses in slabs resting on a stratified semi-infinite solid were performed using a finiteelement computer program. Empirical and theoretical equations for predicting the different values of thermal gradients and the frequency of their occurence were established; these equations are based on Fourier's law and data obtained from observations in Spain. A computer program was developed to obtain new equivalence factors based on the results of the calculations. New conversion formulas for axle loads, corresponding to the fatigue damage criterion adopted, were also developed. This simplified and more realistic design procedure was used to check some of the structural sections included in the Spanish Catalogue of Rigid Pavements. Finally, a new catalog, which takes into consideration the influence of the geometric characteristics of slabs (thickness and length) and the presence of thermal gradients, was proposed. Thermal gradients were estimated using a climatic regionalization of Spain.


It is usual, in structural calculations, to consider two types of stresses: those produced by applied loads (either permanent or variable) and those produced by thermal effects. Normally, these types of stress are computed separately and the results are subsequently added. This procedure is correct for buildings, the support conditions of which are the same for both types of stress. In concrete pavements, however, this is not true because, as is well known, slabs warp as a consequence of thermal gradients, and a part of each one temporarily detaches from the underlying layer. When slabs are warped, deformations produced by traffic loads can reestablish at least partial contact with the lower layer. From a mathematical point of view, the boundary conditions of the problem of calculating stresses and strains in a particular slab with a traffic load and a thermal gradient applied simultaneously are not the same as those that prevail when the two are considered separately. In some cases, it has been proved by

[^0]measurements on existing pavements that the values of stresses calculated by adding individually obtained values are too low.

This problem is of special significance in Spain where climatic variations are very important in many regions and where, in addition, maximum legal single-axle loads are among the highest in the world (1).

Consequently, research was undertaken to calculate the combined effects of traffic loads and thermal gradients on concrete pavements.

This work was divided into two parts. In the first, theoretical phase, the following topics were studied:

- Establishment of a method of determining the frequency and range of thermal gradients in pavement slabs from climatic parameters such as temperature variations and insolation (2).
- Calculation of the maximum stresses produced in a pavement by the simultaneous application of traffic loads and thermal gradients. Because this problem is far from being solved in an analytical way, a computer program (RISC) (3) based on the finite-element method was employed to calculate these stresses in a series of cases. Then, several correlations were set up between the stresses calculated and the different parameters concerned (e.g., thermal gradients, length and thickness of slab).
- Selection of a fatigue law in line with the observed behavior of some Spanish concrete pavements.

There was also a practical part, based on the results obtained in the theoretical one, in which some problems were tackled, taking into account the particular climatic characteristics and load distributions of Spanish roads:

- Definition of a climatic division of Spain, taking into consideration the thermal gradients that occur.
- Definition of an average load and hourly distribution based on measurements taken by portable dynamic scales.
- Establishment of equivalence ratios among different axle loads, which takes into account such factors as climate and slab lengths.
- Establishment of equivalence ratios between an average Spanish truck and a standard axle load of $130 \mathrm{kN}(29,225 \mathrm{lb})$ (maximum single-axle load legally permitted in Spain), also taking into account the previously mentioned factors.
= Devision of the current Spanish Catalogue of Structural Section for Rigid Pavements and proposals for a new one.


## THEORETICAL PHASE

## Method of Calculating Thermal Gradients

Assuming that the quantity of heat absorbed by a body is equal to that released by it, this heat transmission is regulated by Fourier's law:
$d T / d t=\lambda / c \rho\left[\left(\delta^{2} T / \delta_{x}^{2}\right)+\left(\delta^{2} T / \delta_{y}^{2}\right)+\left(\delta^{2} T / \delta_{z}^{2}\right)\right.$
where

```
    T = body temperature ( }\mp@subsup{}{}{\circ}\textrm{C}\mathrm{ ),
t = time (hr),
c = specific heat of the body ( }\textrm{J}/\mp@subsup{\textrm{kg}}{}{0}\textrm{K})\mathrm{ ,
\rho = mass density ( }\textrm{kg}/\mp@subsup{\textrm{cm}}{}{3}\mathrm{ ),
\lambda = thermal conductivity of the body (W/m}\mp@subsup{}{}{0}\textrm{K})
x,y = coordinates in the horizontal plane (m), and
    z = coordinate perpendicular to the plane (x,y)(m).
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If thermal flow inside a horizontal plane is insignificant, Equation 1 can be formulated as
$d T / d t=a d^{2} T / d_{z}{ }^{2}$
If a sinusoidal temperature variation over a period of time is assumed, the solution of Equation 2 can be written as
$T_{z t}=t_{M}+t_{o} \exp (-z \sqrt{\mathrm{II} / a T}) \sin (2 \mathrm{II} t / T-z \sqrt{\mathrm{II} / a T})$
where
$T_{z t}=$ temperature at depth $z$ at instant $t ;$
$t_{M}=$ average temperature of bottom or surface, or both, over an interval of $24 \mathrm{hr}\left({ }^{\circ} \mathrm{C}\right)$;
$t_{o}=$ range of temperature variation in the pavement surface during the 24 -hr interval $\left({ }^{\circ} \mathrm{C}\right)$;
$T=$ period of cyclic variation (86,400-sec daily cycle) in temperature; and
$a=$ diffusivity coefficient $\left(\mathrm{m}^{2} / \mathrm{sec}\right)$.

As shown in Figure 1, the intensity of solar radiation from a cloudless sky increases continuously from sunrise to zenith and then decreases, also at a constant rate, until sundown. The fall in temperature does not end at sundown because thermal energy stored in the pavement is released through its surface throughout the night. Consequently, temperature variations of the pavement surface over a $24-\mathrm{hr}$ period cannot be represented by a single sinusoidal function.

The interval during which temperature increases more or less corresponds to one-half of the sunlight period; the decreasing cycle also includes the night hours. Thus an evident dissymmetry appears in the development of the surface temperatures of the pavement throughout the day and when it is to be described in an analytical way, two expressions must be used, one of them applying to the interval from sunrise to zenith and the other from zenith to the following sunrise.

Consequently, during the interval between sunrise ( $t=0$ ) and zenith ( $t=S_{h}$ ) and in accordance with Equation 3, the following expression can be used to calculate the surface temperature of the pavement:

$$
\begin{equation*}
T_{o t}=t_{M}+t_{o} \sin \left[\mathrm{II}\left(2 t-S_{h}\right) / 2 S_{h}\right] \tag{4}
\end{equation*}
$$

where
$T_{o t}=$ temperature of the surface of the pavement at instant $t$,
$t_{M}=$ average temperature of the surface over a $24-\mathrm{hr}$ period, and
$t_{o}=$ range of temperature variation in the pavement surface over a 24 -hr period ( ${ }^{\circ} \mathrm{C}$ ).


FIGURE 1 Development of air and pavement surface temperature on five consecutive days in summer.

During the time between one zenith and the following sunrise ( $T-\mathrm{S}_{\mathrm{h}}=24 \mathrm{hr}$ ), the surface temperature can be computed by the following formula:
$T_{o t}=t_{M}+t_{o} \sin \left(\left\{\mathrm{II}\left[4\left(t+S_{n}\right)-S_{a}\right]\right\} / 2 S_{a}\right)$
where $S_{n}$ is interval between sundown and sunrise, in hours, and $S_{a}=2\left[S_{h}+S_{n}\right]$.

For these parameters, the following values have been used:

- Summer period: | $S_{h}=10 \mathrm{hr}$ |
| :--- |
|  |
|  |$S_{n}=7 \mathrm{hr}$, Winter period: \(\begin{array}{ll} \& S_{a}=34 \mathrm{hr} <br>

\& S_{n}=8 \mathrm{hr} <br>
\& S_{a}=36 \mathrm{hr} <br>
\& \end{array}\)

At a certain depth (z), extreme values of temperature occur later than they do on the surface. For calculating the temperature variation at depth $z$, the following expressions, similar to Equations 4 and 5 , can be used. A damping factor, representing the thermal inertia of the pavement material, has been introduced.

$$
\begin{align*}
T_{z t}= & t_{M}+t_{o} \exp \left(-z \sqrt{\mathrm{II} / a} S_{z h}\right) \sin \left\{\left[\mathrm{II}\left(2 t-S_{h}\right) / 2 S_{n}\right]\right. \\
& \left.-\left[z \sqrt{\mathrm{II} / a} S_{z h}\right]\right\} \tag{6}
\end{align*}
$$

and

$$
\begin{align*}
T_{z t}= & t_{M}+t_{0} \exp \left(-z \sqrt{\mathrm{II} / a} S_{z a}\right) \sin \left(\left\{\mathrm { II } \left[4\left(t+S_{n}\right)\right.\right.\right. \\
& \left.\left.\left.-S_{a}\right] / 2 S_{a}\right\}-z \sqrt{\mathrm{II} / a} S_{z a}\right) \tag{7}
\end{align*}
$$

where
$S_{z h}=z^{2} S_{h}^{2} / a \pi u_{z}^{2}$
$S_{z a}=z^{2} S_{a}^{2} / a \pi u_{z}^{2}$
and
$u_{z}=(z / 2) \sqrt{T / a \pi}$
It has been assumed that $a=0.31 \times 10^{-8} \mathrm{~m}^{2} / \mathrm{sec}$.
Also, in Expressions 7 and 8,
$t_{M}=t_{A}+t_{l}$,
$t_{A}=$ air temperature $\left({ }^{\circ} \mathrm{C}\right)$,
$t_{I}=$ temperature increase due to insolation $\left({ }^{\circ} \mathrm{C}\right)$,
$t_{o}=\Delta t_{o}+t_{t}$,
$\Delta t_{o}=$ variation of air temperature, and
$t_{I}=\left(0.6 \alpha I_{o} / h\right)-3.9$.
In Formula 10,
$\alpha=$ normal absorptivity, assumed to be equal to 0.65 for heat transfer;
$h=$ pellicular transfer coefficient, assumed to be equal to $20 \mathrm{~W} /{ }^{\circ} \mathrm{Km}^{2}$ for concrete; and
$I_{o}=$ solar constant, equal to $1300 \mathrm{~W} / \mathrm{m}^{2}$.

In Figure 2 the intervals in which Expressions 4, 5, 6, and 7, respectively, apply are represented in a schematic manner.

To make the calculations in connection with these formulas, a computer program (TEMP 1) was developed. To harmonize the results of this program with those of some measurements taken in the field, three coefficients ( $\alpha, \beta$, and $\gamma$ ) were introduced. $\alpha$ is an adjustment coefficient, $\beta$ a corrective wind coefficient, and $\gamma$ a corrective rain coefficient.


FIGURE 2 Domains of validity of Expressions 4-7.

The coefficient $\beta$ is defined by the expression

$$
\begin{equation*}
\beta=\sqrt{(H+C)^{2}+C^{2}} \tag{11}
\end{equation*}
$$

where

$$
\begin{aligned}
H & =\alpha_{h} / \lambda\left(\mathrm{m}^{-1}\right) \\
C & =\sqrt{\mu / a t\left(\mathrm{~m}^{-1}\right)} \\
\alpha_{k} & =7.38+4.91 \times W^{0.75}\left(\mathrm{~W} / \mathrm{m}^{2} \mathrm{O} \mathrm{~K}\right), \text { and } \\
W & =\text { wind speed }(\mathrm{m} / \mathrm{sec})
\end{aligned}
$$

The $\gamma$ coefficient represents the complement of rainy days per thousand.

These coefficients are introduced in calculating $t_{M}$ and $t_{o}$ as follows:
$t_{M}=\left(t_{A}+t_{)}\right) \beta \gamma$
$t_{o}=\left(\Delta t_{o}+t_{p}\right) \beta \gamma(1-\alpha)$

## Computation of Stresses Caused by the Combined Effect of Traffic Loads and Thermal Gradients

To compute the effect of simultaneously applying traffic loads and thermal gradients, several values of some relevant parameters were combined. These values are given in Table 1.

As can be seen in Figure 3, central load position (C) represents a single-wheel, single-axle load placed between two transverse joints. The wheel separation is 182.9 cm between centers, and the distance between the longitudinal joint and the outer wheel center is 45.7 cm . J represents the same load placed tangentially to a transverse joint.

If these load cases are compared with the classic ones studied by Westergaard (4), Case C can be assimilated to a combination of a central load and an edge load and Case J to a combination of an edge load and a corner one.

Of the various cases included in Table 1, those combining traffic loads with zero gradients were used to compare the results provided by the finite-element method with those obtained through other procedures [e.g., the Pickett and Ray influence charts (5)]. Both solutions adapted well.

Moreover, combinations of thermal gradients and zero traffic loads were employed to compare their results with those obtained by means of the Westergaard-BradburyKelley theory. It was found that the solutions supplied by the classic theory are usually underestimates.

TABLE 1 VALUES OF DESIGN PARAMETERS CONSIDERED IN THE STUDY

| Slab <br> Length <br> $(\mathrm{cm})$ | Slab <br> Thickness <br> $(\mathrm{cm})$ | Axle Load <br> $(\mathrm{kN})$ | Load <br> Position | Thermal <br> $\left({ }^{\circ} \mathrm{C} / \mathrm{cm}\right)$ |
| :--- | :--- | :---: | :--- | :--- |
| 350 | 23 | 0 | C | 0 |
| 450 | 25 | 80 | J | 0.3 |
| 550 | 28 | 130 |  | 0.6 |
|  |  | 160 |  | 0.8 |
|  |  |  |  | -0.4 |

It must be pointed out that, through these particular combinations (traffic load with zero gradient and thermal gradient with zero traffic load), it was possible to make a comparison between the stresses resulting from the addition of these values obtained separately for the two cases (as is assumed in some design procedures) and those calculated by considering the simultaneous presence of the same traffic load and the same thermal gradient.

In all cases the concrete slabs were assumed to be resting on a stratified elastic solid composed of the following layers:

- A cement-treated base 15 cm thick,
- A soil-cement subbase also 15 cm thick, and
- A subgrade with an infinite thickness and a California bearing ratio of 5 .

Table 2 gives the maximum values of stresses obtained for the various combinations studied. It must be emphasized that, in order to be on the safe side, a single slab was considered in all cases (i.e., no load transfer through transverse joints was taken into account).

Because the program used requires a considerable amount of computer time, a regression analysis was performed on the results of the different combinations studied. The purpose was to obtain formulas that would give the maximum values of stresses (all expressed in the same way) as a function of the following parameters:

- Axle load $(P)$ in tons,
- Thermal gradient $(\theta)$ in ${ }^{\circ} \mathrm{C} / \mathrm{cm}$, and
- Thickness ( $h$ ) and length $(L)$ of the slabs in cm .


FIGURE 3 Different load positions considered in the study.

TABLE 2 MAXIMUM VALUES OF STRESS (MPa) IN CONCRETE SLABS SUBJECTED TO TRAFFIC LCADS OR THERMAL GRADIENTS, OR BOTH

| Thermal Gradient |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Slab |  | Load Position | $\begin{aligned} & 0^{\circ} \mathrm{C} / \mathrm{cm} \\ & \text { at Axle Load } \\ & \text { (tons) } \end{aligned}$ |  |  | $\begin{aligned} & -0.4^{\circ} \mathrm{C} / \mathrm{cm} \\ & \text { at Axle Load } \\ & \text { (tons) } \end{aligned}$ |  |  |  | $\begin{aligned} & +0.3^{\circ} \mathrm{C} / \mathrm{cm} \\ & \text { at Axle Load } \\ & \text { (tons) } \end{aligned}$ |  |  |  | $\begin{aligned} & +0.6^{\circ} \mathrm{C} / \mathrm{cm} \\ & \text { at Axle Load } \\ & \text { (tons) } \end{aligned}$ |  |  |  | $+0.8^{\circ} \mathrm{C} / \mathrm{cm}$ at Axle Load (tons) |  |  |  |
| Length (cm) | Thickness (cm) |  | 8 | 13 | 16 | 0 | 8 | 13 | 16 | 0 | 8 | 13 | 16 | 0 | 8 | 13 | 16 | 0 | 8 | 13 | 16 |
| 350 | 23 | C | 0.59 | 0.91 | 1.18 | 0.44 | 1.94 | 2.33 | 2.29 | 1.30 | 2.29 | 2.49 | 2.67 | 1.30 | 3.08 | 3.76 | 4.35 |  |  | 4.39 |  |
|  |  | J | 1.17 | 1.68 | 1.81 |  |  | 2.51 |  |  |  | 3.00 |  |  |  | 4.81 |  | 1.20 | 3.69 | 4.39 | 4.77 |
|  | 25 | C | 0.56 | 0.85 | 1.06 | 0.77 | 1.74 | 2.07 | 2.11 | 1.20 | $2 . .00$ | 2.68 | 2.94 | 1.20 | 3.03 | 3.59 | 3.97 | 1.20 | 4.39 | 5.17 | 5.76 |
|  |  | J | 1.01 | 1.57 | 1.72 | 0.77 | 2.03 | 2.64 | 2.66 |  | 2.62 | 2.93 |  |  | 3.29 | 4.56 | 5.02 |  |  | 4.33 |  |
|  | 28 | C | 0.49 | 0.80 | 1.03 | 0.70 | 1.70 | 1.91 | 2.05 | 1.10 | 1.96 | 2.48 | 2.89 | 1.30 | 3.00 | 3.46 | 3.78 |  |  | 4.33 |  |
|  |  | J | 0.88 | 1.37 | 1.65 |  |  | 2.53 |  |  |  | 2.83 |  |  |  | 3.61 |  |  |  | 4.92 |  |
| 450 | 23 | C | 0.59 | 1.06 | 1.33 | 1.55 | 1.96 | 2.49 | 2.52 | 1.28 | 2.43 | 2.74 | 3.04 | 1.89 | 3.38 | 4.10 | 4.67 |  |  | 5.29 |  |
|  |  | J | 1.13 | 1.68 | 2.04 |  |  | 2.49 |  |  |  | 2.95 |  |  |  | 4.81 |  | 1.70 | 4.41 | 4.90 | 5.28 |
|  | 25 | C | 0.52 | 0.83 | 1.16 | 1.73 | 2.06 | 2.42 | 2.46 | 1.37 | 2.18 | 2.79 | 3.03 | 1.70 | 3.44 | 3.94 | 4.37 | 1.70 | 4.38 | 4.49 | 5.93 |
|  |  | J | 1.00 | 1.57 | 1.97 |  | 2.46 | 2.57 | 2.70 | 1.37 | 2.51 | 2.75 | 3.37 | 1.70 | 3.17 | 4.41 | 5.01 |  |  | 4.95 |  |
|  | 28 | C | 0.47 | 0.76 | 0.94 | 1.73 | 2.06 | 2.34 | 2.53 | 1.45 | 2.28 | 2.70 | 3.06 | 1.54 | 3.38 | 3.90 | 4.23 |  |  | 4.86 |  |
|  |  | J | 0.85 | 1.40 | 1.51 |  |  | 2.74 |  |  |  | 1.98 |  |  |  | 3.73 |  |  |  | 5.00 |  |
| 550 | 23 | C | 0.65 | 1.05 | 1.34 | 2.10 | 2.40 | 2.62 | 2.46 | 1.31 | 2.38 | 2.76 | 2.47 | 2.48 | 3.56 | 4.30 | 4.87 |  |  | 5.05 |  |
|  |  | J | 1.18 | 1.68 | 2.05 |  |  | 2.51 |  |  |  | 2.90 |  |  |  | 4.64 |  |  | 4.57 | 5.06 | 5.46 |
|  | 25 | C | 0.56 | 0.92 | 1.16 | 2.20 | 2.20 | 2.29 | 2.46 | 1.42 | 2.39 | 2.99 | 2.68 | 2.35 | 3.48 | 4.09 | 4.52 | 2.35 | 4.48 | 5.16 | 5.74 |
|  |  | J | 0.99 | 1.57 | 1.97 |  | 2.60 | 2.77 | 2.63 | 1.42 | 2.63 | 2.83 | 3.73 | 2.35 | 2.65 | 4.41 | 5.05 |  |  | 5.24 |  |
|  | 28 | C | 0.50 | 0.82 | 1.03 | 2.03 | 2.10 | 2.16 | 2.40 | 1.52 | 2.27 | 2.77 | 3.19 | 2.13 | 3.60 | 4.03 | 4.36 |  |  | 4.87 |  |
|  |  | J | 0.89 |  | 1.63 |  |  | 2.60 |  |  |  | 1.97 |  |  |  | 3.86 |  |  |  |  |  |

Note: $\mathrm{C}=$ central load position and $\mathrm{J}=$ joint load position.

Stresses calculated by these formulas are expressed in MPa. Several types of correlations were studied both for the central load position and for the joint one. Exponential formulas provided the best results, and they are included hereafter, as are the correlation coefficients ( $R \mathrm{~s}$ ) obtained in each case.

1. Traffic loads without gradients:

Central load position
$\sigma_{c}=e^{0.356}\left(P^{1.046} L^{0.128} / h^{1.219}\right)$
( $R=0.985$ )
Joint load position
$\sigma_{j}=e^{2.042}\left(P^{0.802} L^{0.0403} / h^{1.215}\right)$
( $R=0.890$ )
2. Traffic loads and thermal gradients:

Central load position
$\sigma_{c}=e^{-0.193}\left(P^{0.36} L^{0.25} \theta^{0.589} / h^{0.18}\right)$
( $R=0.956$ )
Joint load position
$\sigma_{j}=e^{3.503}\left(P^{0.357} L^{-0.079} \theta^{0.507} / h^{0.701}\right)$
( $R=0.886$ )
3. Thermal gradients without traffic loads:

Central load position
$\sigma_{c}=e^{-6.113}\left(L^{1.125} \theta^{0.319} / h^{0.028}\right)$
( $R=0.886$ )
In this last case, the formula deduced for the joint load position does not have a correlation coefficient similar to the previous ones, and for this reason it has not been included.

As can be seen, the proposed formulas provide very good correlations for the central load position. As far as the joint position is concerned, the accuracy of the adjustment is also most striking but less satisfactory.


FIGURE 4 Finite-element mesh and critical points for the load positions considered.

As was to be expected, the slab points at which the maximum stresses occur vary with the case in question. These points are shown in Figure 4 which also shows the finiteelement mesh employed in the computer program.

Tables 3-5 give the values of stresses $\sigma_{x}$ and $\sigma_{y}$ (parallel to the edges) at these particular points and also the maximum stress. Usually, this is parallel to one edge or joint, or very close to it.

Table 6 gives a comparison between the stresses obtained considering the simultaneous effect of a traffic load and a thermal gradient and the values that result from adding the stresses obtained when each factor is considered separately. In the authors' opinion, the results in this table are one of the most interesting findings of the present work.

As can be seen, in virtually all the cases considered in Table 6 the stresses obtained for a traffic load and a thermal gradient applied at the same time are clearly greater than the sum of the stresses calculated separately. As a consequence, the results obtained by the latter procedure, and employed in some design procedures, are unsafe.

Table 7 gives the percentage of rates between the stresses computed by these two procedures. As can be seen, these rates are very high in most cases and have a great effect on design calculations.

An analysis of the stresses shows that, for an axle load equal to 130 kN , maximum values are obtained when this load is placed near a transverse joint, which is in keeping with Westergaard's theory (4).

However, differences between the stresses resulting from central and joint positions of the axle load (a very important factor when there are no gradients) decrease when the gradients increase. Even for gradients of about $+0.3^{\circ} \mathrm{C} / \mathrm{cm}$, stresses caused by axle loads on the so-called central position are slightly higher than those caused by the same load placed near a transverse joint.

## Adjustment of a Fatigue Law

Because the only damage factor considered in the present work was pavement fatigue, an essential step was to adapt a fatigue law suitable for the concrete. As is well known, this problem can be regarded as still unsolved (6). A great many researchers have dealt with fatigue phenomena of concrete under bending, and they have proposed different laws that give inconsistent results when compared. After different possibilities were analyzed, the following fatigue law, which takes into account the ratio between the maximum and the minimum applied stresses, was proposed:
$\log _{10} N F=11\left[1-\left(\sigma_{\max } / M R\right)\right] /(1-R)$
where
$N F=$ number of loading cycles producing failure; $\sigma_{\text {max }}=$ maximum applied stress;
$M R=$ modulus of rupture of the concrete at 28 days (thirdpoint loading method) increased by 10 percent to consider strength gain with age;

TABLE 3 MAXIMUM VALUES OF STRESSES (MPa) AT CRITICAL POINTS (central load position)

| Point | $\begin{aligned} & \theta=0^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=13 \mathrm{t} \end{aligned}$ |  |  | $\begin{aligned} & \theta=-0.4^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=13 \mathrm{t} \end{aligned}$ |  |  | $\begin{aligned} & \theta=+0.3^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=13 \mathrm{t} \end{aligned}$ |  |  | $\begin{aligned} & \theta=+0.6^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=13 \mathrm{~T} \end{aligned}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $x, y)$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\max }$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\max }$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ |
| $\begin{aligned} & \mathrm{A}^{a} \\ & (\mathrm{~L} / 2,3 \mathrm{H} / 8) \end{aligned}$ | -0.76 | 0.07 | -0.76 | 1.01 | 2.41 | 2.41 | -1.36 | -2.05 | -2.05 | -2.97 | $-1.67$ | -2.98 |
| $\begin{aligned} & \mathrm{B} \\ & (\mathrm{~L} / 2, \mathrm{H} / 8) \end{aligned}$ | -0.83 |  | -0.83 | 0.10 | 0.76 | 0.82 | -1.74 | -2.77 | $-2.77$ | -3.95 | -1.92 | -3.95 |

NOTE: Negative values correspond to tension in bottom fibers.
${ }^{a} \mathrm{~L},=$ slab length $(4.57 \mathrm{~m}) ; \mathrm{H}=$ slab width $(3.66 \mathrm{~m})$.

TABLE 4 MAXIMUM VALUES OF STRESSES (MPa) AT CRITICAL POINTS (joint load position)

| Point (coordinates $x, y$ ) | $\begin{aligned} & \theta=0^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=13 \mathrm{t} \end{aligned}$ |  |  | $\begin{aligned} & \theta=-0.4^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=13 \mathrm{t} \end{aligned}$ |  |  | $\begin{aligned} & \theta=+0.3^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=13 \mathrm{t} \end{aligned}$ |  |  | $\begin{aligned} & \theta=+0.6^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=13 \mathrm{~T} \end{aligned}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ |
| $C^{\text {a }}$ |  |  |  |  |  |  |  |  |  |  |  |  |
| (L, H/8) | -0.13 | -1.56 | $-1.57$ | 0.05 | -0.95 | $-1.04$ | $-2.28$ | $-2.35$ | $-2.35$ | -0.43 | -3.43 | $-3.52$ |
| Cl |  |  |  |  |  |  |  |  |  |  |  |  |
| (L, 5H/8) | -0.12 | -1.48 | $-1.52$ | -0.12 | -0.96 | $-1.02$ | -2.23 | $-2.76$ | $-2.76$ | -0.39 | -4.39 | -4.39 |
| $\begin{aligned} & \mathrm{E} \\ & (0.7 \mathrm{~L}, \mathrm{H} / 2) \end{aligned}$ | 0.52 | 0.09 | 0.52 | 2.61 | 2.20 | 2.61 | -0.75 | -1.03 | $-1.03$ | -1.13 | $-1.30$ | -1.35 |

Note: Negative values correspond to tension in bottom fibers.
$a_{\mathrm{L}}=$ slà lengelī ( 4.57 m ); $\mathrm{H}=$ slàt width $(3.66 \mathrm{~m})$.

TABLE 5 MAXIMUM VALUES OF STRESSES (MPa) AT CRITICAL POINTS IN SLAB SUBJECTED ONLY TO THERMAL GRADIENTS

| Point (coordinates $x, y$ ) | $\begin{aligned} & \theta=-0.4^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=0 \mathrm{t} \end{aligned}$ |  |  | $\begin{aligned} & \theta=+0.3^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=0 \mathrm{t} \end{aligned}$ |  |  | $\begin{aligned} \theta & =+0.6^{\circ} \mathrm{C} / \mathrm{cm} \\ P & =0 \mathrm{t} \end{aligned}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\max }$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ |
| $\begin{aligned} & \mathrm{A}^{a} \\ & (\mathrm{~L} / 2,3 \mathrm{H} / 8) \\ & { }_{\mathbf{B}} \end{aligned}$ | 1.33 | 0.80 | 1.33 | -1.13 | -0.71 | -1.13 | -1.40 | -0.53 | -1.40 |
| $\begin{aligned} & (\mathrm{L} / 2, \mathrm{H} / 8) \\ & \mathrm{C} \end{aligned}$ | 0.84 | 0.03 | 0.84 | -1.26 | -0.26 | -1.26 | -1.59 | -0.25 | $-1.59$ |
| $\begin{aligned} & (\mathrm{L}, \mathrm{H} / 8) \\ & \mathrm{Cl} \end{aligned}$ | 0.02 | 0.12 | 0.12 | -0.11 | -0.67 | -0.78 | -0.13 | -0.75 | -0.91 |
| (L, 5H/8) | 0.005 | 0.2 | 0.2 | -0.07 | -1.16 | -1.16 | -0.08 | $-1.26$ | $-1.27$ |
| $\begin{aligned} & \mathrm{E} \\ & (0.7 \mathrm{~L}, \mathrm{H} / 2) \end{aligned}$ | 0.65 | 0.87 | 0.88 | -0.94 | -0.85 | -0.94 | -1.17 | -0.85 | -1.18 |
| $\begin{aligned} & \mathrm{A} 1 \\ & (\mathrm{~L} / 2, \mathrm{H} / 2) \end{aligned}$ | 1.72 | 1.37 | 1.72 | -1.11 | -0.78 | -1.11 | -1.38 | -0.76 | -1.38 |
| $\begin{aligned} & \mathrm{B1} \\ & (\mathrm{~L} / 2,0) \end{aligned}$ | 0.75 | -0.00 | 0.75 | -1.37 | -0.62 | -1.37 | -1.70 | -0.06 | $-1.70$ |

Note: Negative values correspond to tension in bottom fibers.
$a_{L}=$ slab length ( 4.57 m ); $\mathrm{H}=$ slab width $(3.66 \mathrm{~m})$.

$$
\begin{aligned}
R & =\sigma_{\min } / \sigma_{\max }, \\
\sigma_{\min } & =\text { minimum stress; and } \\
\sigma_{\max } & =\text { maximum stress } .
\end{aligned}
$$

For instance, when the pavement is subjected to a certain
thermal gradient, $\sigma_{\text {min }}$ is the stress due to this gradient and $\sigma_{\max }$ the stress caused by the combined effect of this gradient and a traffic load.

The numerical coefficient 11 included in Expression 19 differs slightly from those proposed by other researchers

TABLE 6 COMPARISON OF STRESSES OBTAINED IN DIFFERENT CASES.

| Point <br> (coordinates <br> $x, y$ ) | $\begin{aligned} & \theta=-0.4^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=130 \mathrm{kN} \end{aligned}$ |  |  | $\begin{aligned} & \theta=-0.4^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=130 \mathrm{kN} \end{aligned}$ |  |  | $\begin{aligned} & \theta=+0.6^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=130 \mathrm{kN} \end{aligned}$ |  |  | $\begin{aligned} & \theta=+0.6^{\circ} \mathrm{C} / \mathrm{cm} \\ & P=130 \mathrm{kN} \end{aligned}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\text {max }}$ |
| Central Load Position |  |  |  |  |  |  |  |  |  |  |  |  |
|  | $\underbrace{p}$ |  |  | $\sim+x^{x^{p}}$ |  |  |  |  |  | $\infty+\underbrace{p^{p}}$ |  |  |
| $\begin{aligned} & \mathrm{A}^{a} \\ & (\mathrm{~L} / 2,3 \mathrm{H} / 8) \\ & \mathrm{B} \end{aligned}$ | 1.04 | 2.41 | 2.42 | 0.57 | 0.87 | 0.87 | -2.97 | -1.67 | -2.98 | -2.17 | 0.46 | -2.17 |
| (L/2, H/8) | 0.102 | 0.76 | 0.82 | 0.01 | -0.07 | -0.07 | -3.95 | -1.92 | -3.95 | -2.39 | -0.35 | -2.39 |


| Joint Load Position |  |  |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| C |  |  |  |  |  |  |  |  |  |  |  |  |
| (L, H/8) | 0.05 | -0.95 | -1.04 | -0.11 | -1.44 | -1.44 | -0.43 | -3.43 | $-3.52$ | -0.26 | -2.31 | -2.31 |
| C1 |  |  |  |  |  |  |  |  |  |  |  |  |
| L, 5H/8) | -0.12 | -0.96 | -1.02 | -0.012 | -1.20 | $-1.20$ | -0.39 | -4.39 | -4.41 | -0.20 | $-2.78$ | $-2.78$ |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| $(0.7 \mathrm{~L}, \mathrm{H} / 2)$ | 2.61 | 2.14 | 2.61 | 1.17 | 0.97 | 1.17 | -1.13 | -1.30 | -1.35 | -0.66 | -0.76 | -0.76 |

NOTE: Negative values correspond to tension in bottom fibers.
$a_{\mathrm{L}}=$ slab length $(4.57 \mathrm{~m}) ; \mathrm{H}=$ slab width $(3.66 \mathrm{~m})$.
TABLE 7 INCREASES IN THE STRESSES OBTAINED BY SIMULTANEOUS ACTION OF TRAFFIC LOADS AND THERMAL GRADIENTS COMPARED WITH THOSE OBTAINED SEPARATELY

|  |  |  | Stress Increase |  |
| :--- | :--- | :--- | :--- | :--- |
| Load <br> $(\mathrm{kN})$ | Load <br> Position | Thermal <br> Gradient <br> $\left({ }^{\circ} \mathrm{C} / \mathrm{cm}\right)$ | Absolute <br> $(\mathrm{MPa})$ | Percentage |
| 130 | C | -0.4 | 1.55 | 278 |
| 130 | C | +0.6 | 0.81 | 137 |
| 130 | J | -0.4 | 1.44 | 224 |
| 130 | J | +0.6 | 1.62 | 158 |

NOTE: $\quad C=$ central load position; $\mathbf{J}=$ joint load position.
[e.g., Domenichini and Marchiona (6)]. It was obtained by adjustment in order to match the fatigue law to the field behavior of several Spanish concrete pavements:

- Some stretches of the Mediterranean Motorway are situated in a region with a mild, maritime climate. The concrete pavements are composed of slabs that are 25 cm thick and variable in length. They are subjected to average daily traffic (ADT) of about 10,000 vehicles, and the proportion of heavy vehicles amounts to 20 percent. The largest slabs, 500 cm long, began to crack 6 years after they were opened to traffic,
- The Villalobas Bypass on National Highway 301 is situated in a continental climatic zone and subjected to an ADT of 16,000 vehicles, with 25 percent heavy vehicles. The concrete pavement is 23 cm thick with transverse joints placed at varying intervals. Cracking in the largest slabs, 600 cm long, was observed as early as only 6 months and 1 year after they were opened to traffic.


## PRACTICAL WORK

As an application of the theoretical results obtained in the first part of this work, some of the subjects included in the current Spanish standard (6-2-IC) for the design of rigid pavements were evaluated. In consideration of the different climatic zones in Spain and the composition of the traffic, the following items were analyzed:

- The equivalence factors between axle loads: the current Spanish standard assumed the fourth-power law established from the results of the AASHO test;
- The damaging factor of an average Spanish truck, expressed in terms of standard axles of 130 kN : the current Spanish standard recommends an equivalence of 0.5 standard axle per average commercial vehicle; and
- The structural sections proposed in this standard.

To perform these practical applications, two prior analyses had to be carried out:

- A climatic division of Spain on the basis of the occurrence of thermal gradients and
- An evaluation of the "aggressiveness" of the average Spanish traffic on the national network, taking into account the axle load range, which was obtained with the help of portable dynamic scales.


## Climatic Division of Spain Based on the Occurrence of Thermal Gradients

To establish climatic divisions, data collected by the National Meteorological Service were analyzed, using July and

December data as representative of the average for winter and summer periods, respectively. The following parameters were considered:

- Average air temperature $\left(t_{A}\right)$ and its daily variation about the mean $\left(\Delta t_{A}\right)$;
- Average number of rainy days taken into account in the $\gamma$ coefficient of the formulas; and
- Wind speed, which influences the $\beta$ coefficient.

On the basis of the analysis of these data, Spain was divided into three climatic zones called maritime, standard continental, and extreme continental, respectively. They are characterized by the parameters given in Table 8.

By introducing these values into Expressions 4-7 and grouping them together, the percentages for the occurrence of gradients are obtained for the different climatic zones (Table 9). It must be pointed out, however, that the values given in this table can only be considered a first approach. More accurate calculations would require field measurements and correlation of the results with temperature variations, pluviometry, wind regime, cloudiness, and so forth.

## Traffic Load Distribution

To calculate the effect of traffic, the results of a measuring campaign with dynamic scales carried out on several Spanish roads were used. The following traffic load distributions were obtained:

1. The results of traffic distribution by axle load are given in Table 10. It was assumed that this distribution was constant throughout the day.
2. Hourly distribution of traffic.

The results that represent the mean hourly distribution, expressed in terms of ADT percentage, are given in Table 11. The results presented are the average of those for six roads located in the main network.

## Combined Distribution of Traffic Load and Thermal Gradients

The combined distribution of the thermal gradients that
TABLE 8 CHARACTERISTIC PARAMETERS

| Climate | Parameter |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | ${ }^{t} A$ | $\Delta t_{A}$ | $\alpha$ | $\beta$ | $Y$ |
| Marine |  |  |  |  |  |
| Summer | $26^{\circ} \mathrm{C}$ | $\pm 6^{\circ} \mathrm{C}$ | 0.4 | 0.736 | 1.0 |
| Winter | $12^{\circ} \mathrm{C}$ | $\pm 5^{\circ} \mathrm{C}$ | 0.6 | 0.845 | 0.3 |
| Standard continental |  |  |  |  |  |
| Summer | $28^{\circ} \mathrm{C}$ | $\pm 8^{\circ} \mathrm{C}$ | 0.35 | 0.736 | 1.0 |
| Winter | $6^{\circ} \mathrm{C}$ | $\pm 4^{\circ} \mathrm{C}$ | 1.0 | 0.845 | 0.2 |
| Extreme continental |  |  |  |  |  |
| Summer | $28^{\circ} \mathrm{C}$ | $\pm 8^{\circ} \mathrm{C}$ | 0.1 | 0.850 | 1.0 |
| Winter | $3^{\circ} \mathrm{C}$ | $\pm 6^{\circ} \mathrm{C}$ | -2.0 | 0.845 | 0.2 |

occur throughout the year in the different climatic zones and the hourly distribution of traffic are given in Table 12.

## Equivalence Factors Between Different Axle Loads Taking into Consideration Climate and Slab Lengths

As was seen previously, the damaging effect of axle loads depends on whether or not they are combined with thermal gradients. In the absence of gradients, the correlations deduced show an acceptable linearity between the applied loads and the resultant stresses: The exponent of load $P$ in Expressions 13 and 14 is close to 1 . However, when a thermal gradient occurs, this linearity disappears; the exponent of load $P$ takes on values of about 0.36 in Expressions 15 and 16. Consequently it is impossible to establish a single equivalence factor between two different axle loads, as adopted in a simplified way in Spanish standard 6-2-IC. Even the slight corrections in these equivalence factors introduced by the AASHO Interim Guide for the Design of Pavements that only takes into account slab thickness can give incorrect results.

If a relationship in the shape of a power law is adopted
$N_{i} \times P_{i}{ }^{Y}=N_{j} \times P_{j}{ }^{Y}$

TABLE 9 PERCENTAGES OF OCCURRENCE OF THERMAL GRADIENTS

| Interval of Thermal Gradient ( ${ }^{\circ} \mathrm{C} / \mathrm{cm}$ ) | Climate |  |  |
| :---: | :---: | :---: | :---: |
|  |  | Standard | Extreme |
|  | Maritime | Continental | Continental |
| -0.2 to +0.2 | 56.93 | 56.21 | 37.50 |
| +0.2 to +0.4 | 16.66 | 15.97 | 16.66 |
| +0.4 to +0.5 | 2.08 | 3.13 | 5.02 |
| +0.5 to +0.6 | 2.08 | 3.13 | 5.02 |
| +0.6 to +0.8 | 0.25 | 0.375 | 0.50 |
| -0.2 to -0.4 | 22.00 | 21.185 | 34.94 |
| Total | 100.00 | 100.00 | 100.00 |

TABLE 10 TRAFFIC DISTRIBUTION BY AXLE LOADS

| Axle Load <br> Interval <br> $(\mathrm{kN})$ | Percentage |
| :--- | :---: |
| $0-20$ | 51.910 |
| $20-40$ | 8.510 |
| $40-60$ | 15.780 |
| $60-80$ | 10.470 |
| $80-100$ | 4.970 |
| $100-120$ | 4.090 |
| $120-140$ | 3.090 |
| $140-160$ | 1.050 |
| $160-180$ | 0.102 |
| $180-200$ | 0.089 |
| Total | 100.000 |

TABLE 11 AVERAGE HOURLY DISTRIBUTION OF COMMERCIAL TRAFFIC

| Hour | ADT <br> Percentage |
| :--- | :--- |
| $9-10$ | 6.69 |
| $10-11$ | 6.78 |
| $11-12$ | 6.88 |
| $12-13$ | 5.23 |
| $13-14$ | 5.92 |
| $14-15$ | 5.43 |
| $15-16$ | 4.63 |
| $16-17$ | 5.98 |
| $17-18$ | 6.11 |
| $18-19$ | 6.90 |
| $19-20$ | 6.55 |
| $20-21$ | 4.99 |
| $21-22$ | 4.64 |
| $22-23$ | 3.00 |
| $23-24$ | 1.80 |
| $0-1$ |  |
| $1-2$ | 1.37 |
| $2-3$ | 0.87 |
| $3-4$ | 0.64 |
| $4-5$ | 0.74 |
| $5-6$ | 0.85 |
| $6-7$ | 1.37 |
| $7-8$ | 2.13 |
| $8-9$ | 4.70 |
| Total | 5.79 |
|  | 100.00 |
|  |  |

TABLE 12 COMBINED DISTRIBUTION OF TRAFFIC AND THERMAL GRADIENTS

| Gradient <br> Interval <br> ( ${ }^{\circ} \mathrm{C} / \mathrm{cm}$ ) | Gradient Adopted in Calculations ( ${ }^{\circ} \mathrm{C} / \mathrm{cm}$ ) | ADT (\%) |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  |  | Maritime Climate | Standard Continental Climate | Extreme Continental Climate |
| -0.2 to 0.2 | 0.0 | 60.65 | 57.05 | 46.11 |
| 0.2 to 0.4 | 0.2 | 17.75 | 16.21 | 20.49 |
| 0.4 to 0.5 | 0.4 | 2.22 | 3.18 | 6.17 |
| 0.5 to 0.6 | 0.5 | 2.22 | 3.18 | 6.17 |
| 0.6 to 0.8 | 0.6 | 0.27 | 0.38 | 0.61 |
| -0.2 to -0.4 | -0.4 | 16.89 | 20.00 | 20.45 |
| Total |  | 100.00 | 100.00 | 100.00 |

exponent $\gamma$ can present quite marked differences depending not only on the thickness of the slab but also on its length in the particular climatic zone where the pavement is situated and even on the bending strength of the concrete.

Table 13 gives the values of exponent $\gamma$, taking as reference a standard axle of 130 kN and taking into account the previously mentioned parameters. These values range from 5.7 to 12.6 ; therefore, it takes considerably higher values than the value of 4 usually admitted.

The figures in Table 13 constitute another proof of the great influence of overloading on pavement behavior. The longer the slabs, the more pronounced is its influence.

TABLE 13 EQUIVALENCE FACTORS: VALUES OF $\gamma$ EXPONENT IN THE EQUATION $(P / 130)^{\gamma}$
( $P=$ Azle Load and Standard Axle Load $=130 \mathrm{kN}$ )

| $\begin{aligned} & \mathrm{L} \\ & (\mathrm{~cm}) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \\ & (\mathrm{~cm}) \end{aligned}$ | Climate |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Maritime |  | Standard Continental |  | Extreme Continental |  |
|  |  | MR1 | MR2 | MR1 | MR2 | MR1 | MR2 |
| 350 | 21 | 5.5 | 7.0 | 6.3 | 7.2 | 5.9 | 6.9 |
|  | 23 | 5.7 | 6.5 | 5.9 | 6.8 | 5.7 | 6.7 |
|  | 25 | 5.4 | 6.2 | 5.7 | 6.5 | 5.6 | 6.6 |
|  | 28 | 5.4 | 6.1 | 5.6 | 7.2 | 5.7 | 6.6 |
| 400 | 21 | 5.6 | 7.4 | 6.6 | 7.6 | 6.4 | 7.6 |
|  | 23 | 6.1 | 7.0 | 6.3 | 7.3 | 6.2 | 7.4 |
|  | 25 | 5.9 | 6.8 | 6.2 | 7.3 | 6.6 | 7.3 |
|  | 28 | 6.0 | 6.9 | 6.3 | 7.2 | 6.6 | 7.6 |
| 450 | 21 | 5.7 | 7.8 | 7.0 | 8.2 | 6.9 | 8.3 |
|  | 23 | 6.4 | 7.5 | 6.7 | 7.9 | 6.9 | 8.3 |
|  | 25 | 6.4 | 7.5 | 6.8 | 7.9 | 7.1 | 8.4 |
|  | 28 | 7.0 | 8.0 | 7.3 | 8.3 | 7.7 | 8.8 |
| 500 | 21 | 5.8 | 8.4 | 7.5 | 9.0 | 7.7 | 9.4 |
|  | 23 | 6.9 | 8.3 | 7.4 | 8.8 | 7.7 | 9.4 |
|  | 25 | 7.1 | 8.4 | 7.6 | 9.0 | 8.1 | 9.6 |
|  | 28 | 8.3 | 9.5 | 8.6 | 9.9 | 9.1 | 10.5 |
| 550 | 21 | 5.9 | 9.4 | 8.2 | 10.1 | 8.6 | 10.8 |
|  | 23 | 7.6 | 9.3 | 8.2 | 10.0 | 8.8 | 10.8 |
|  | 25 | 8.0 | 9.7 | 8.6 | 10.4 | 9.3 | 11.2 |
|  | 28 | 10.2 | 11.7 | 10.5 | 12.0 | 11.0 | 12.6 |

Note: $L=$ slab length, $H=$ slab thickness, $M R 1, M R 2=$ modulus of rupture of the concrete, equal to 5.0 MPa and 4.5 MPa , respectively

## CONCLUSIONS

1. The effects of the simultaneous action of traffic loads and thermal gradients do not correspond to the sum of traffic stresses and thermal stresses. When a pavement slab is curled downward the stresses due to traffic loads are greater than the sum of the thermal stresses and traffic stresses calculated separately. If the slab is curled upward, the stresses produced by the simultaneous action of thermal gradient and traffic loads are similar to or greater than the sum of the stresses calculated separately. Consequently, current design procedure is inadequate.
2. The length of slabs is an important parameter that must be considered in the design of pavements. The greatest fatigue damage occurs during the simultaneous action of traffic loads and thermal gradient when the latter value equals or exceeds $0.6^{\circ} \mathrm{C} / \mathrm{cm}$. Consequently, the equivalence factors between axle loads are functions of the thickness and length of the slabs and depend on the frequency and value of the thermal gradients.
3. The equivalence between axle loads can be expressed by a relation like the AASHO equation, in which the exponent $\gamma$ ranges between 5.5 and 12.6. $\gamma$ depends on the geometric characteristics of the slabs, the climatic conditions of the environment, and the modulus of rupture of concrete.

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