Load Transfer in Undoweled Transverse Joints of PCC Pavements

M. Poblete, R. Valenzuela, and R. Salsilli

The results of load transfer evaluations in 21 test sections of the Chilean in-service highway network are presented. Characteristics of transverse joints are described, and procedures to measure the absolute deflections of four points in a slab, plus another one across the transverse joint, are explained. The procedures allow load transfer to be evaluated with good accuracy and repeatability. Measurements conducted over continuous 24-hr cycles in winter and summer show that the load transfer depends upon the thermal conditions of the pavement. Its daily variations are satisfactorily explained by the changes in transverse joint openings. Load transfer on the leave slab is much different from that on the approach slab, unless the joint stiffness is so high that the pavement behaves as a continuous strip. To evaluate internal stresses of pavement slabs, a mechanistic approach is described in which three kinds of joint stiffnesses are proposed to take into account the effects of shear forces and moments developed at joints, as well as compressions built up by the slabs' moisture and temperature.

In undoweled PCC pavements, traffic-induced stresses in the slabs depend highly upon the capacity of structural collaboration of the neighboring slabs, through the interlocking developed at transverse and longitudinal joints. The eventual deterioration of the load transfer implies a progressive increase in internal stresses, and thus slab cracking could be initiated after fewer load repetitions. Consequently, load transfer is usually considered a variable of the pavement condition (*1*–*4*), although its value would not be unique because of its dependence on thermal conditions as well as on load position, either upon the approach slab or the leave slab (*5*).

In view of the general observations of slab upward curlings in the Chilean portland cement concrete (PCC) pavements, varying with the daytime thermal gradients (see another paper in this Record by Poblete et al.), attention was paid to what was simultaneously occurring at transverse joints. In fact, the cycles of variation in mean temperatures across slab thickness produced longitudinal contractions and elongations that caused changes in transverse joint openings; at low temperatures, the pavement behaves as a set of relatively isolated slabs, whereas on very hot days, the pavement behaves as a continuous strip, with complete locking of joints.

The results presented herein are part of extensive research on Chile's concrete pavement network, with the ultimate objective of modeling the structural deterioration of in-service concrete pavements designed and constructed under general AASHTO guides and specifications. Survey and measurement methodologies were periodically performed at 21 locations on the PCC paved highway network where a significant rainfall gradient from north to south and moderate thermal variations are encountered. In each of the 21 test sections, sensors were installed to measure the temperature distribution across the slab thickness, as well as deep reference bases (DRBs) for measuring absolute vertical displacements of slabs (Fig. 1). Furthermore, reference bases were installed at joints to measure horizontal movements and faulting.

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To evaluate the load transfer (LT) or, strictly speaking, the efficiency of transverse joints, several expressions have been defined to relate the simultaneous deflections of adjoining edges produced by the traffic loads usually positioned on the approach slab:

$$LT_A = 2\delta_2/(\delta_1 + \delta_2) \quad (1)$$

$$LT_D = \delta_2/\delta_1 \quad (2)$$

$$LT_E = (\delta_1 - \delta_1') + (\delta_2' - \delta_2) \quad (3)$$

where

δ_1, δ_2 = simultaneous deflections at the approach and leave edge, respectively, when the load is on the approach slab, and

δ_1', δ_2' = simultaneous deflections at the approach and leave edges, respectively, when the load is on the leave slab.

Equation 3, developed by the AIPCR Technical Committee (*3*) to characterize the load transfer in pavements on eroded bases, considers the deflections at transverse edges with both positions of loading, and the present work shows that LT values may differ according to the variation in boundary conditions for the estimation of internal stresses. However, Equation 3 will not be used in the discussions below. Equation 1 from Teller and Sutherland (*1*) and Equation 2 from Darter (*2*) are used because they are simpler and better serve the purposes of the paper.

TRANSVERSE JOINT CHARACTERISTICS

Transverse joints of Chilean pavements are spaced 3.5–5.5 m apart, skewed with a slant between 0 and 1/6, and the jointing is accomplished by inserting fiber strips and/or sawing to a depth of about one-fourth of the slab thickness. No dowels or other means of load transfer have been implemented.

The joint efficiency is therefore only the result of interlocking between the irregular faces of joint cracks that are formed with large roughnesses around the high-hardness si-

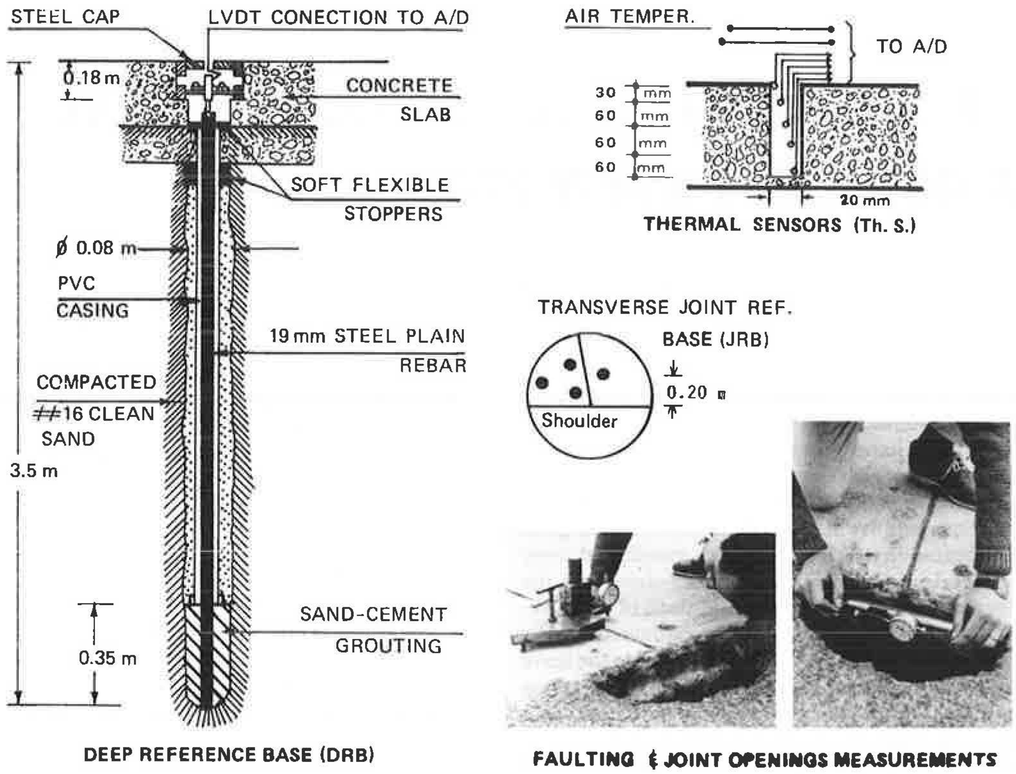


FIGURE 1 Instrumentation devices in the test sections.

liceous aggregates. In general, joint cracks are subvertical with preferential inclination to one side.

Joint materialization is gradual, starting with great spacings on the order of one every three or more nominal slabs during the first hours of concrete age. In Figure 2(a), the variations in openings are shown for 10 consecutive joints measured after 16 days in a test section having reference bases installed in the fresh concrete. At a later age, as shown in Figure 2(b), when all joints are activated, the openings tend to be evenly distributed among the joints. The joints that cracked first, however, can still be identified by openings that are greater, even after several years of service.

For evaluating the joint efficiency, the most open among 10 consecutive joints was selected. Its variation in opening over a daily cycle is representative of the average variation for the whole set of joints.

DEFLECTIONS BY LOAD

In order to measure the slab displacements caused by traffic loads and by the internal temperature variations, four DRBs were installed in the leave slab plus another one in the approach slab at 0.50 m from the outer edge, just to evaluate the joint efficiency, as illustrated in Figure 3. Every base has a steel bar grouted in the subsoil 3.5 m beneath the pavement, and it is isolated from lateral confinement by a PVC casing. Absolute deflections of the loaded slabs are recorded with ±0.01 mm accuracy by means of an analog/digital system. The five simultaneous deflection signals are processed and monitored in the field along with the internal temperature signals, which are measured continuously at five levels in the slab with ±0.2°C accuracy.

In Figure 4, typical recordings are presented for the simultaneous deflections of DRB border points 1, 2, 5, 3 and DRB center point 4 as the loaded truck moves slowly from the approach to the leave track with respect to the joint. Results correspond to measurements at test section No. 1 for two thermal conditions on a summer day. In the graphs, two maxima represent the deflections of the point upon passage of the front axle and then of the rear axle; also, some rocking of the slabs is detectable from the negative deflections produced by the rear axle pressing the opposite edge of the leave slab. To better illustrate the rocking of slabs with partial support, a similar recording is shown in Figure 5, obtained at test section No. 14 during a cold-winter-day cycle when the joints' efficiency is minimal. From both graphs, it can be deduced that the deflections are always elastic and that for the thermal state of negative gradient (slab surface cooler than bottom), the slabs rock around its supported central zone, whereas DRB points 1, 2, 3, and 5 lift up when the loaded axles press on the slab near the far edge with respect to the DRB point under consideration. For the thermal state of strong positive gradient, the deflections at the same points are minimal and represent the elastic deformation of the supported slab edges by the action of the loaded axle.

On the other hand, comparison of the recordings of representative points DRB 1 and DRB 2 for the negative gradient shows a different behavior between both sets of slabs, which is due to the varying degrees of upward curling as well as to the interlocking at joint faces. In another paper in this Record,

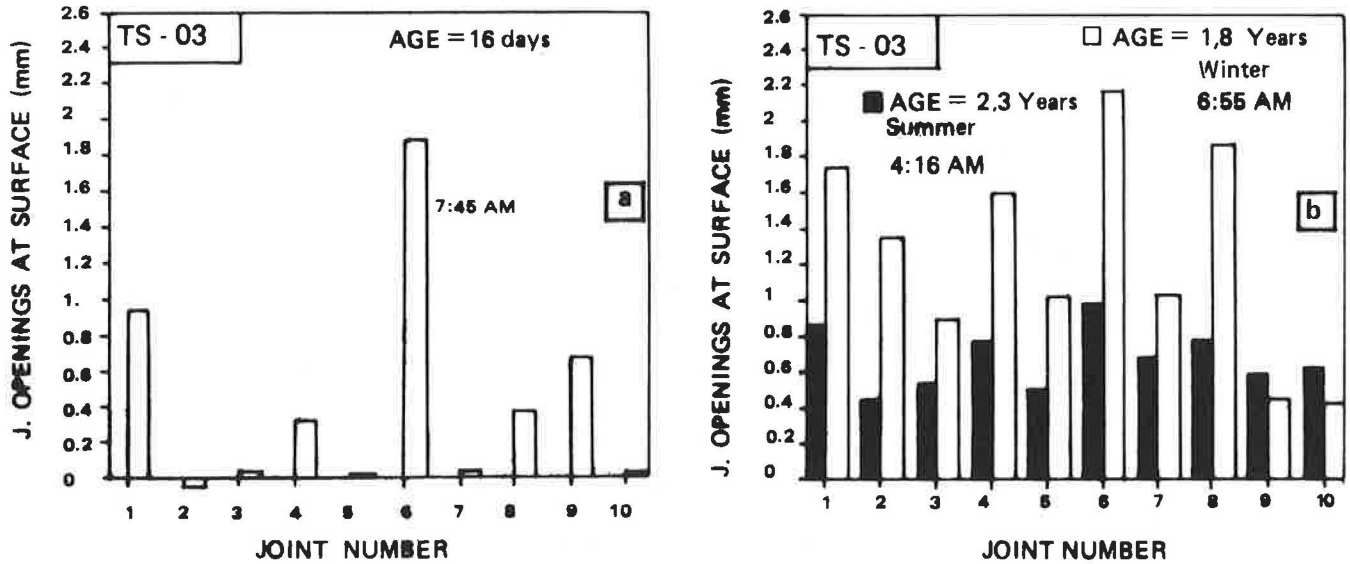


FIGURE 2 Active joints after (a) 16 days and (b) 2 years of age.

Poblete et al. show that the influence of geometrical differences between slabs is of very reduced significance.

In Figure 6, the maximum deflections at points DRB 1 and DRB 2 are plotted against corner uplifts for complete 24-hr thermal cycles during winter and summer days, and are considered representative of the general behavior of all 21 test-section pavements. In winter the deflection is linear with the magnitude of corner uplifting; in summer a similar tendency is recorded, but in a narrow loop. The difference observed between the heating and cooling is related to the joint face interlock due to different compressions of the lower transverse edges. The different loops observed at DRB points 1 and 2

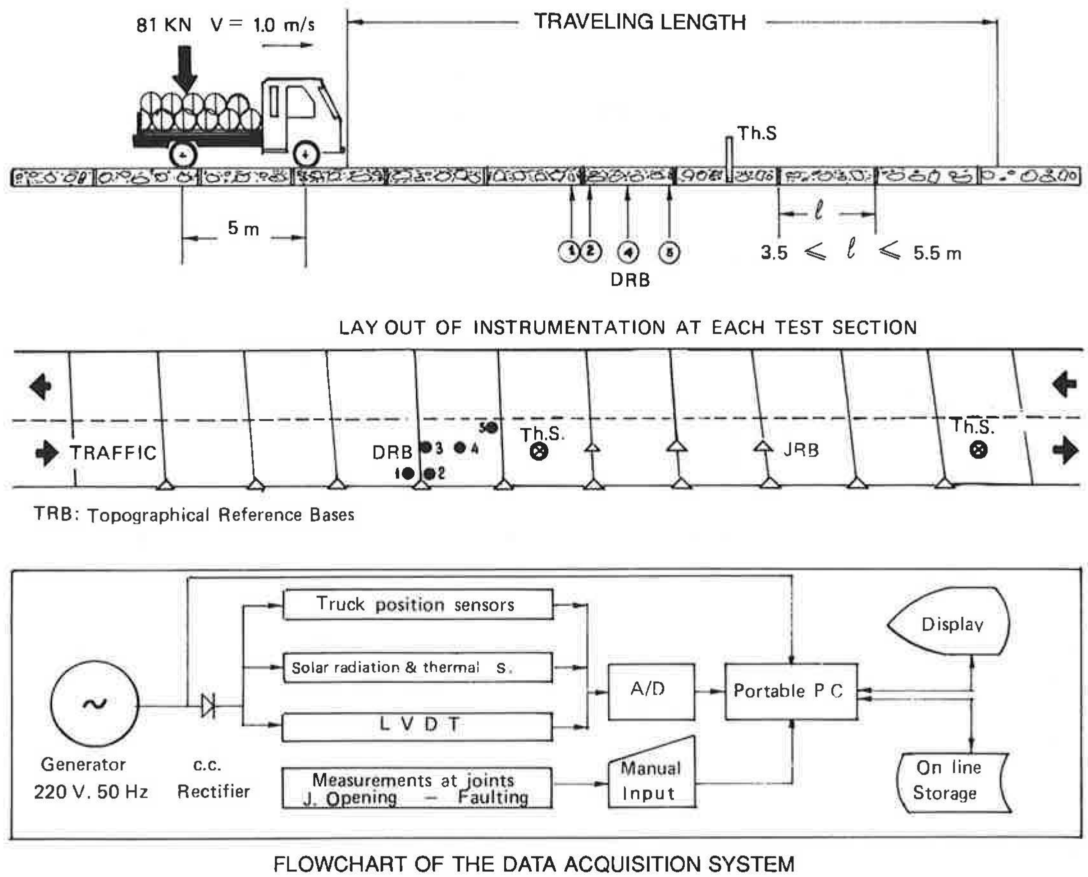


FIGURE 3 Schematic layout of instrumentation.

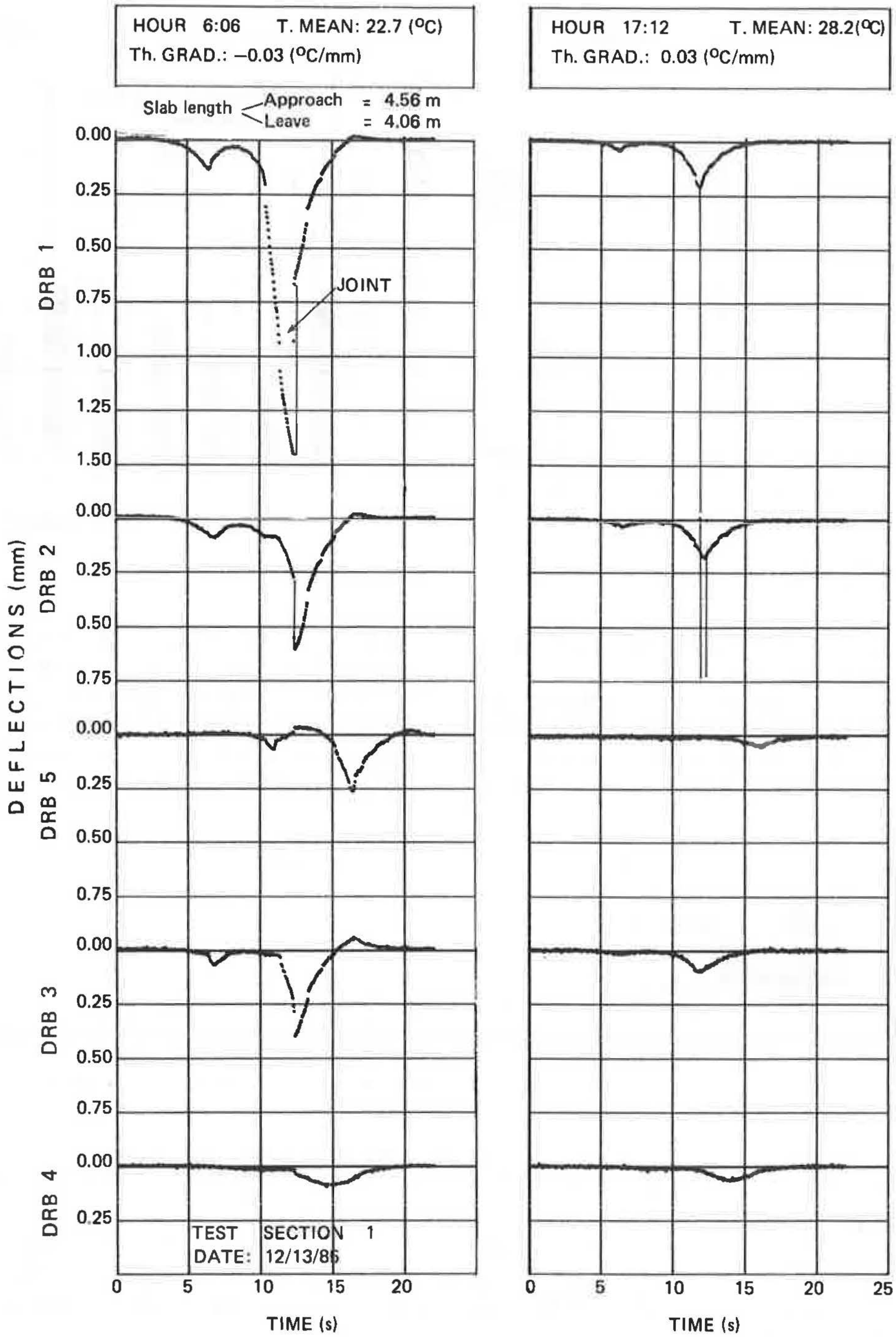


FIGURE 4 Simultaneous deflections under traveling load for two temperature conditions in summer.

suggest that the joint efficiency is different when the load is either on the approach slab or on the leave slab. In any case, the thermal deformations are relative to the minimum day value, so, according to the other work of Poblete et al. in this Record, in summer this reference could be considered as "full support" of slab edges, including some sinking into the base, whereas in winter this condition, which is seldom reached, makes the deflections appear higher.

In all pavement sections included in this study, a generalized prevailing upward curling of the slabs, causing considerable lack of support at edges, has been verified (Figure 7a). Under high temperatures and associated strong positive gradients, that condition may be reversed, with the slabs expanded and a cylindrical downward curling imposed on the slabs with their longitudinal edges supported (Figure 7c). The condition in which a plain slab is supported under each point occurs only when the slab temperature causes a change from upward to downward curling and vice versa.

Further discussions of this behavior can be found in another paper by Poblete et al. in this Record.

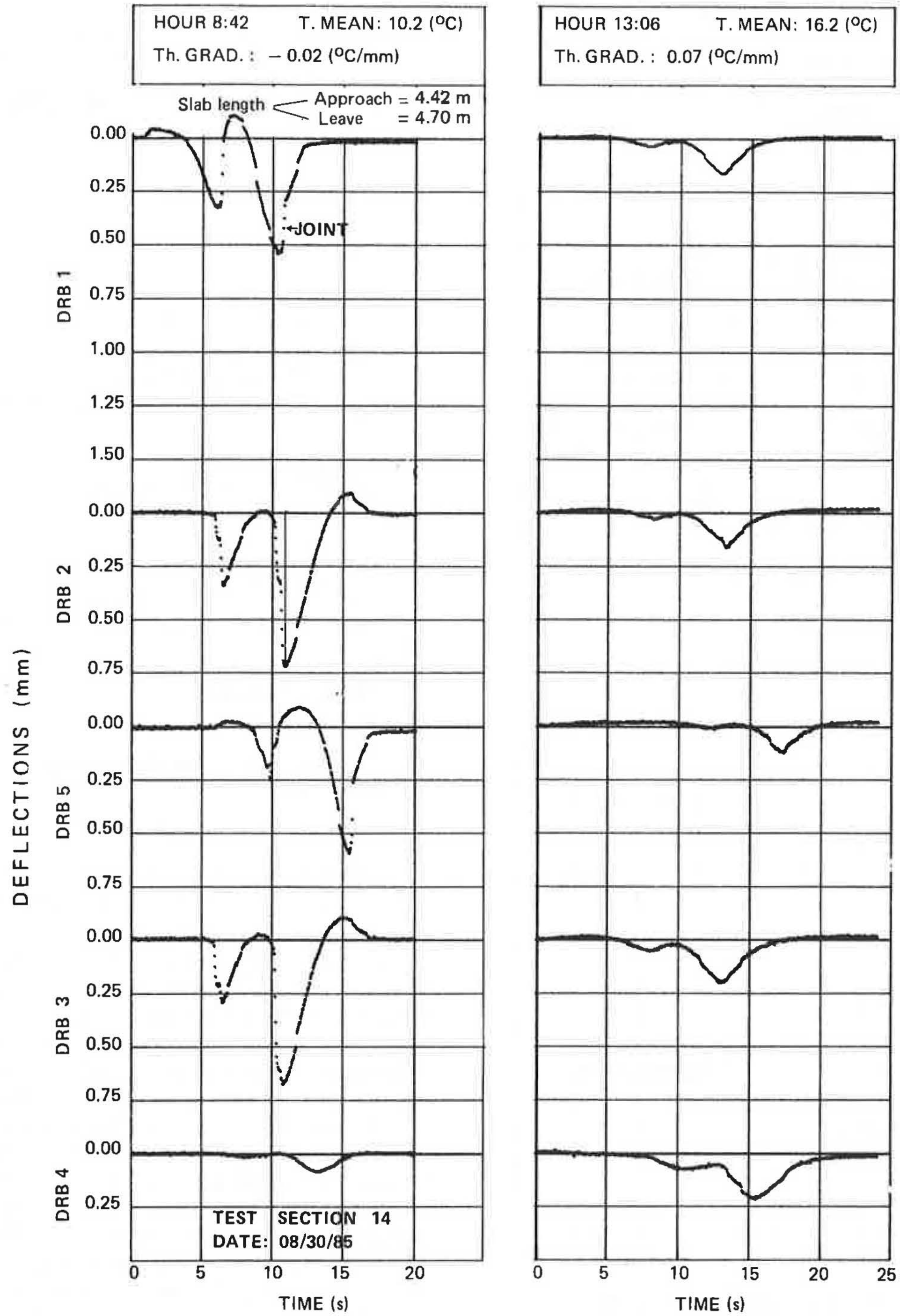


FIGURE 5 Simultaneous deflections under traveling load for two temperature conditions in winter.

LOAD TRANSFER EVALUATIONS

By substituting the simultaneous deflections obtained from the recordings of DRB points 1 and 2 at two representative test sections into Equation 1, load transfer LT_A can be evaluated for different positions of the load. As shown in Figure 8(a) and (b), each of the four curves represents diverse thermal conditions during a 24-hr measurement cycle. As an additional reference, the equivalent LT_D is included on the right ordinate of the graphs. The load transfer is different for each thermal state and decreases with the distance to the joint. Moreover, the computed LT is different whether the load is on the leave slab (LT_{leave}) or on the approach slab ($LT_{approach}$) with a discontinuity in the joint itself due to differential upliftings of the transverse edges. In such cases, the loaded axle may be intercepting the joint, or the tire treads may be pressing on both edges. In any case, the deflections when the load is too close to the joint are distorted and the corresponding LT values may be erroneous.

All measurements were performed with a truck carrying

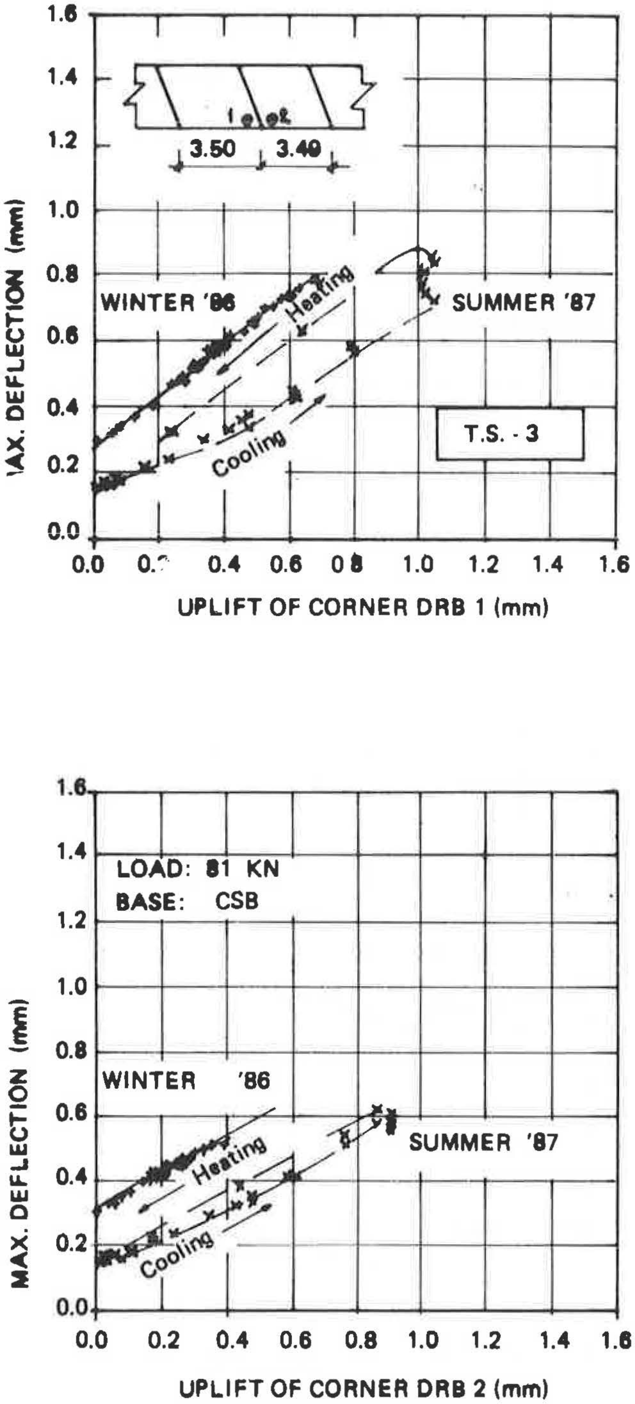


FIGURE 6 Slab corner displacements and maximum deflections during winter and summer day cycles.

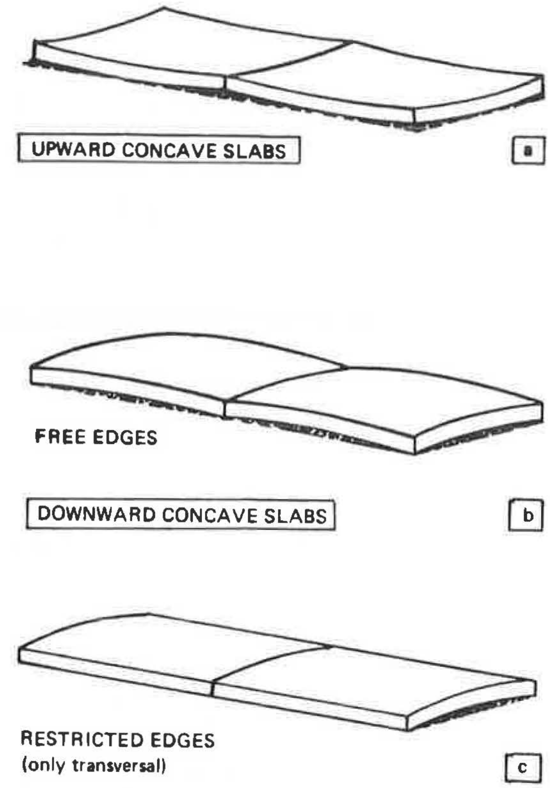


FIGURE 7 Shapes of slabs deformed by temperature.

about 80 kN (18 kips) on the rear axle, which is the pavement design load; however, in some cases, measurements at the maximum legal load (110 kN) were also obtained, but no significant differences in the LT values computed from either recording were noted (*6*). In all cases, outer rear wheels pass exactly on point DRB 1 and thereafter on point DRB 2, so that the truck path is somewhat displaced toward the shoulder.

In Figures 9 and 10 the LT computed with the load on DRB points 1 and 2 is presented for two test sections exhibiting typical behavior. The results emphasize the differences between LT_{approach} and LT_{leave} over a daily thermal cycle.

To explain this behavior, a detailed analysis of the influence of slab internal temperatures on the joint interlockings is made. In fact, in the other paper by Poblete et al. in this Record, it was shown that for negative gradients (slab surface cooler than the bottom) the transverse joints may be relatively open if the mean temperature is low and the joint faces are free to rotate due to thermal gradients, so that the contact between slabs is limited to the lower transverse edges. On the other hand, the lower edges may be strongly compressed if the mean temperature is high, resulting in a high mobilization of shear strength at the joint, as illustrated in Figure 11. This effect is maximized when the joint becomes locked by the concurrence of a positive gradient and a high enough mean temperature, where the pavement behaves as a continuous strip.

In the case of the summer cycle shown in Figure 9, there is a moment in the day when the values for LT_{approach} and LT_{leave} converge because of a quick heating of the slab surface without a significant increase in the mean temperature across the slab thickness. This behavior is interpreted as a decompression of the lower transverse edges when the joint faces have a tendency to be mutually parallel. As a consequence, it is not uncommon for the lower edges to break after a number of loading cycles. This has been observed in core samples drilled along the induced joint cracks of medium-aged pavements. Breakage of the lower edges would cause a rapid deterioration of the load transfer; therefore LT_{approach} and LT_{leave} would coincide at last in a residual unique value.

For a better appraisal of these same effects, the influence

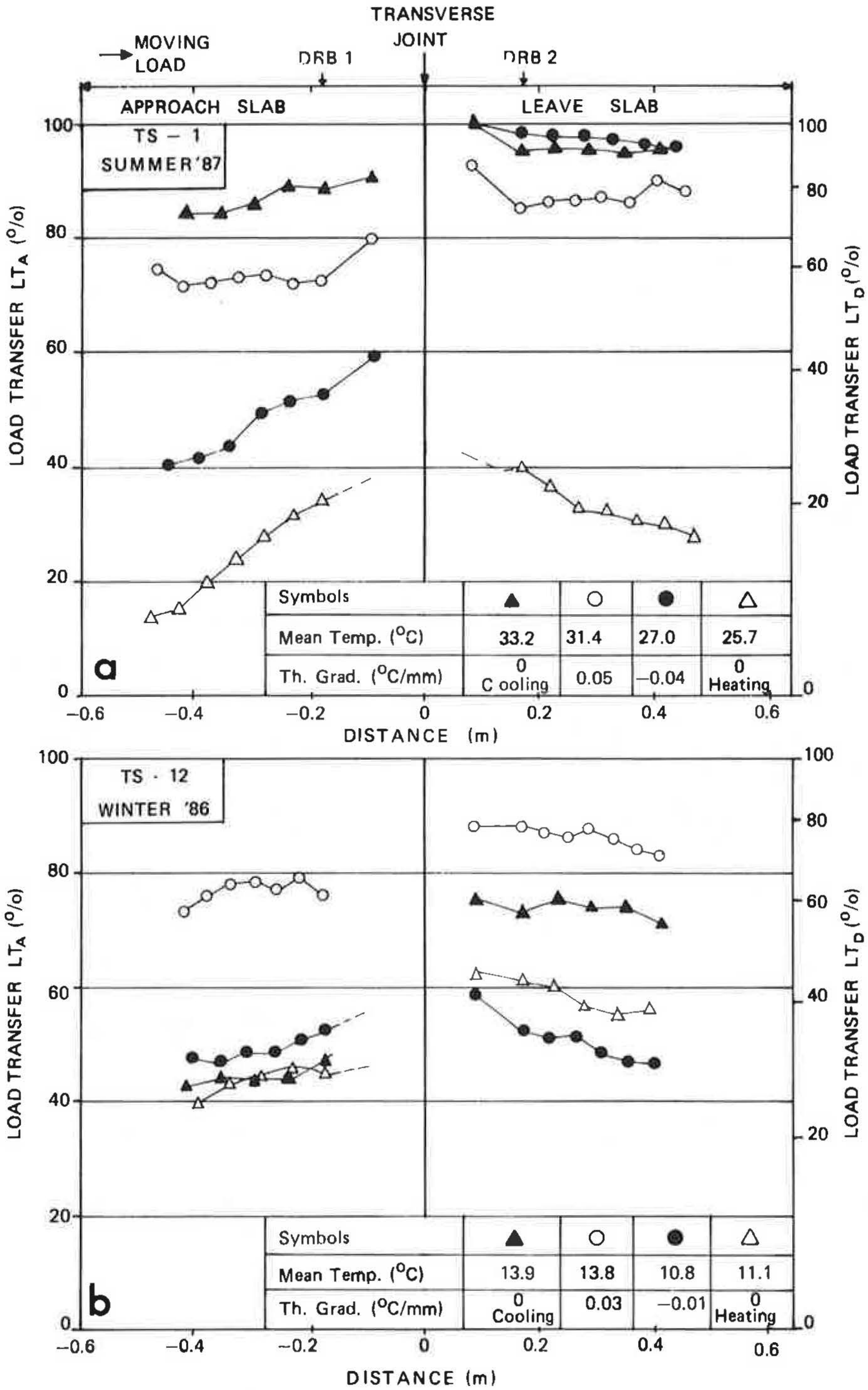


FIGURE 8 Load transfer evaluated for different positions of an 81-kN moving load over a 24-hr measurement period in (a) summer and (b) winter.

of joint openings on $LT_{approach}$ and LT_{leave} is illustrated in Figure 12 for two thermal cycles on a sunny summer day at a representative test section. From the analysis of $LT_{approach}$, different load transfers may be observed whether in the heating or in the cooling curves, and in both, generally a lower load transfer corresponds to a greater opening. Differences at equal openings are explained again by the different compressions at the lower transverse edges.

Some differences between heating and cooling are also present in the curves for LT_{leave} and can be explained by similar reasoning. However, comparison with $LT_{approach}$ discloses substantial differences, which may be attributed to a preferent inclination of the induced crack (Figure 13). Every time a loaded slab can rest on the favorably inclined edge of an adjoining slab, a good load transfer will result, independently from the joint opening. If the two consecutive summers of Figure 12 are compared, the different load transfers obtained for similar openings and thermal conditions imply a de-

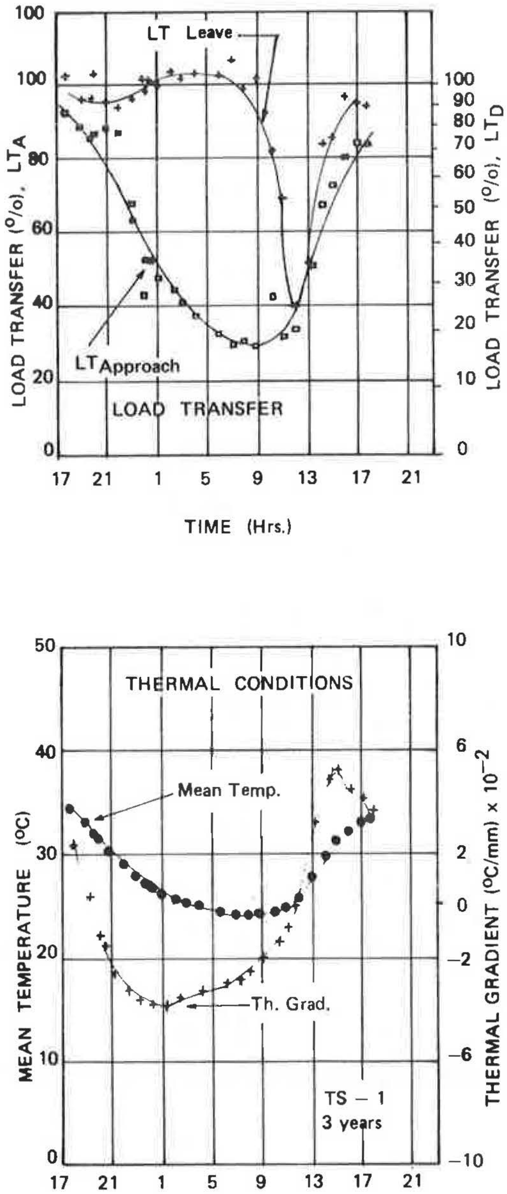


FIGURE 9 Variation of load transfer during a summer day cycle.

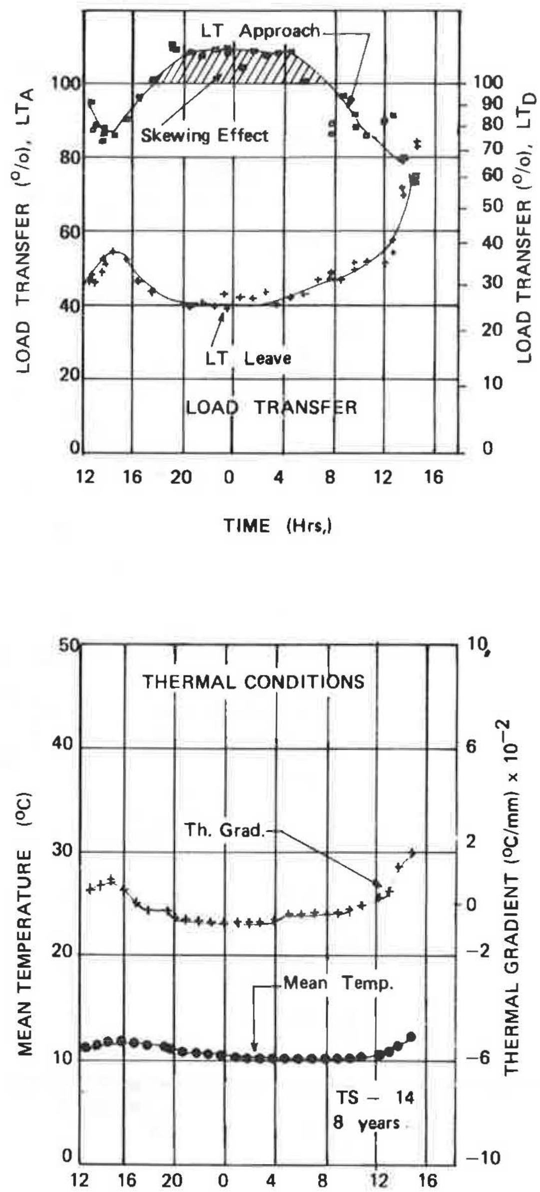


FIGURE 10 Variation of load transfer during a winter day cycle.

terioration of the joint interlocking by fracture of some roughnesses.

Table 1 summarizes the $LT_{approach}$ and LT_{leave} pairs estimated for the time at which one of them is lowest on the day of measurement; the duration of that condition is also estimated. In all winter cases the minimum characteristic load transfer is low during most of the day, and particularly during morning hours. In summer the minimum characteristic load transfer is usually much higher, occasionally over 90 percent, and not infrequently lasts the whole day. Such seasonal differences are due to the greater opening of the joints during the lower winter temperatures, except in test sections 11, 15, 19, and 21. In those sections the load transfer seems to remain high throughout the year, in spite of the large temperature differences prevailing between winter and summer days. The high load transfer may be attributable to the low locking temperature of the joints at these test sections, which were paved under cold and humid ambient conditions, and to the swelling of concrete during winter (7). Finally, the values of Table 1 represent the load transfers of a single joint selected at each test section as the most open among a set of 10 consecutive joints and which is expected to open further over time (Figure 2b). For this reason the actual load transfers at the other joints should be somewhat higher under similar thermal conditions.

CONSIDERATIONS FOR JOINT STIFFNESS MODELING

To model the deterioration of Chilean concrete pavements, a mechanistic approach is taken. To this end, stresses caused by real traffic and environmental loads are evaluated by a

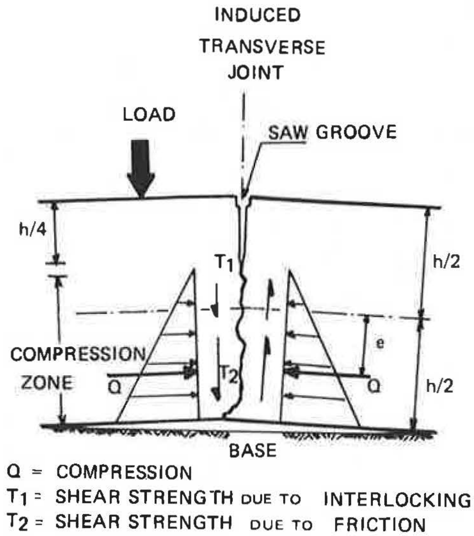


FIGURE 11 Forces acting on an undoweled transverse joint.

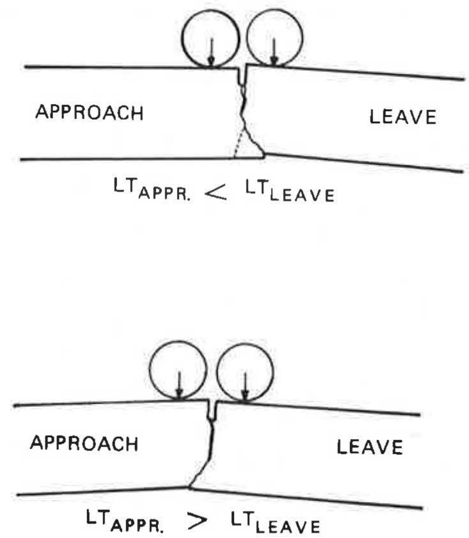
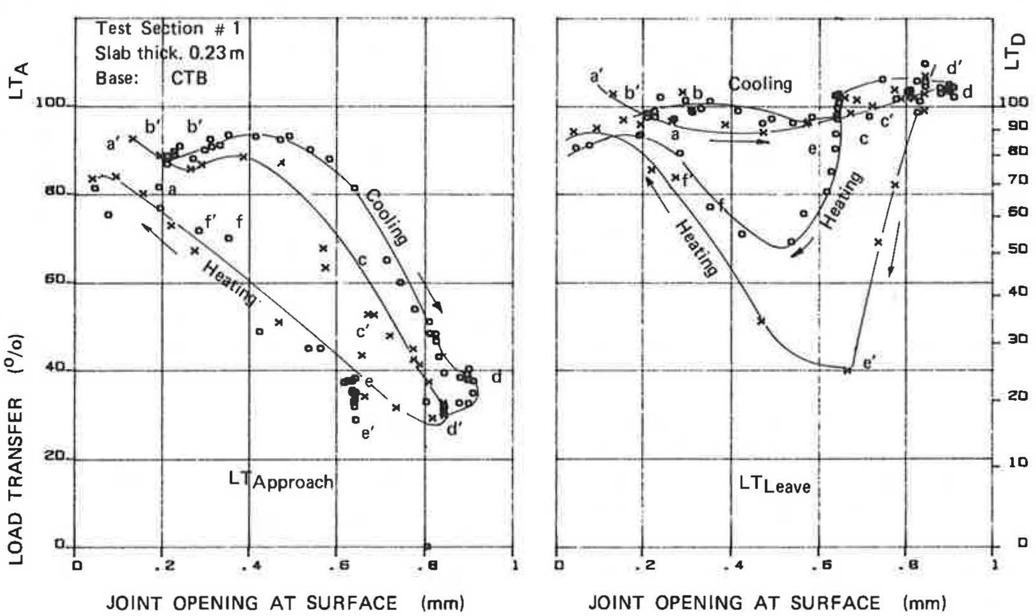


FIGURE 13 Hypothesized crack inclination in induced transverse joints.

finite-element method. The pavement is modeled as a set of three slabs with realistic boundary conditions of partial support, such as discussed in preceding paragraphs in the analysis of deflection results. With regard to the transverse joints and longitudinal borders of the slabs, their actual conditions require that they be discussed separately.

At longitudinal borders, a free edge is evident in the contact with the granular shoulder. In many Chilean pavements, the other border behaves practically as a free edge, up to the relatively high level of deflections necessary to mobilize the eventual collaboration of the adjacent slabs through the keyed joint (*8*). In other cases some partial load transfer may be accounted for at this border.

At the transverse edges the restraints can be broken down as illustrated in Figure 11, with an eccentric compression Q depending on the slab temperature, an associated shear strength T_1 of frictional nature, and the aggregate interlocking shear strength T_2. The eccentricity, e, is minimal for the uncurled (plain) slabs and increases with the upward curling caused by rotation of the transverse edges. Both magnitudes Q



Point		a	b	c	d	e	f
Th. Grad.	°C/mm	0.04	0.0	- 0.04	- 0.03	0.0	0.03
M. Temp.	°C	32.2	31.0	26.3	22.7	23.9	26.4
		□ SUMMER 1986					

a'	b'	c'	d'	e'	f'
0.02	0.0	−0.04	−0.03	0.0	0.05
34.6	33.2	26.1	24.1	25.7	30.0
x SUMMER 1987					

FIGURE 12 Influence of joint openings on load transfer.

TABLE 1 LOAD TRANSFER EVALUATED FOR AN 81-kN MOVING LOAD

Test Section		Slab thick. (m)	Skew. (m)	Thermal Cond. Mean. Temp. (°C)	Thermal Cond. Thermal Grad. (°C/mm)	LT_A (%) Approach	LT_A (%) Leave	Duration (hrs)	Thermal Cond. Mean. Temp. (°C)	Thermal Cond. Thermal Grad. (°C/mm)	LT_A (%) Approach	LT_A (%) Leave	Duration (hrs)
Longotoma	1	0.23	+0.46	11.5	-0.02	40	40	14	22.5 24.5	-0.03 -0.03	30 30	100 100	16 16
Las Chilcas	2	0.23	+.046	12.0	-0.04	55	80	24	28.5	-0.05	95	100	24
Lampa	3	0.24	+0.74	9.0	-0.02	50	70	14	26.5	-0.05	60	100	7
Lo Vásquez	4	0.26	+0.46	6.5	-0.03	45	45	14	23.0 23.7	-0.05 -0.05	55 40	100 85	16 12
Talagante	5	0.22	+0.53	12.0	0.00	90	30	---	25.5	-0.06	95	95	24
Paine	6	0.24	+0.66	7.0	-0.03	50	100	17	25.5	-0.04	95	95	24
Graneros	7	0.25	+0.66	8.5	-0.04	35	100	16	23.5 25.0	-0.06 -0.05	95 95	95 100	24 24
San Fernando	8	0.23	-0.55	9.0	-0.01	65	35	16	25.0 22.5	-0.04 -0.05	70 90	95 80	5 7
San Rafael	9	0.23	+0.41	12.5	0.00	50	80	24	25.5 23.0	-0.06 -0.05	95 95	100 100	24 24
Cocharcas	10	0.21	+0.71	11.7	-0.03	70	40	10					
Concepción	11	0.23	0.00	13.0	-0.01	90	90	12	23.5	-0.04	90	95	6
Cabrero	12	0.22	-0.66	11.0	-0.02	50	60	10	28.0	-0.04	100	95	24
Laja	13	0.21	0.00	9.3	-0.02	0 - 30	75	14	26.0	-0.06	95	85	14
C. Esperanza	14	0.21	+0.59	10.0	-0.01	100	45	14	26.5	-0.06	90	90	14
Victoria	15	0.23	+0.75	9.5	-0.01	95	100	24	23.0	-0.03	95	00	24
Temuco	16	0.21	+0.59	11.5	0.00	60	75	14	23.0	-0.03	90	90	24
Gorbea	17	0.22	+0.42	9.0	-0.02	55	80	8	23.0	-0.04	95	95	24
Loncoche	18	0.22	+0.79	4.5	-0.02	45	80	6	17.2	-0.05	95	95	24
Mariquina	19	0.23	+0.84	2.8	-0.03	80	100	14	23.0	-0.04	95	00	24
Mafil	20	0.23	+0.59	5.1	-0.02	70	45	20	23.1	-0.04	70	95	4
Rio Bueno	21	0.22	+0.62	3.2	-0.04	85	100	24	24.0	-0.03	80	85	6
Skewing		+ forward - backward		WINTER 1986					SUMMER 1986 & 1987				

and e are functions of the initial joint openings, of the drying shrinkage, and of the thermal expansion of the pavement slabs, going from a maximum value during the afternoon hours of sunny summer days to an uncertain low value on cold nights.

The shear restrictions, $T_1 + T_2$, developed at transverse joints during loading involve the concept of joint stiffness, very similar to that considered in the model proposed by Armaghani et al. (9), with the possible difference that the compression Q should be considered explicitly, since the compressional stress in the slab plane helps to diminish the tensile stresses at the slab surface (8). Hence, three kinds of joint stiffnesses at transverse edges are proposed:

$$K_h = Q/\Delta m \tag{4}$$

$$K_z = (T_1 + T_2)\Delta z = (\tau + \beta Q)/\Delta z \tag{5}$$

$$K_\theta - M/\Delta\theta - Qe/\Delta\theta \tag{6}$$

where

- Δm = joint opening variation evaluated at middle plane of joint,
- $\Delta\theta$ = relative rotation between adjacent edges,
- Δz = relative vertical displacement between adjacent edges = $|\delta_1 - \delta_2|$, and
- τ, β = coefficients.

For each specific application, the numerical processes need to be treated in successive iterations, comparing the calculated displacements with those actually measured at the joints and at DRB points 1, 2, 3, 4, and 5 under equivalent loads.

The steps include an initial process of a single slab stressed by a corrected negative thermal gradient that takes into account the existence of a permanent upward curling. The slab is modeled as a thick plate resting on continuous subgrade springs, whose K_s value is back-calculated after adjusting the real compressed area of the support. The next step is to analyze three slabs linked together with joint springs and stressed by the same temperature gradient, whose calculated joint openings and rotations permit, by comparison with those measured, the adjustment of numerical values for K_h, K_z and K_θ. These stiffnesses are to be fed in successive steps, when processing slabs with the axle loads actually used for the deflection measurements. In these final steps some further adjustments of the stiffnesses may be necessary.

The full processing of test-section pavements, with application of the boundary conditions that have been discussed, is under way, and the resulting stresses as well as details of the complete models being used will be presented in future papers.

CONCLUSIONS

The methodology used for the measurement of absolute deflections, whose results are presented herein, allows the evaluation of the load transfer at joints with good accuracy and repeatability, under real traffic and in any thermal condition of the pavement.

The results obtained at 21 test sections confirm the conclusion that load transfer is not constant along a daily cycle but depends on the thermal conditions of the pavement. For each particular case the daily variation is satisfactorily explained in terms of the variations in transverse joint openings; no other variables such as slab thickness and base type were identified as a significant influence.

Load transfer computed from deflections with the load upon the leave slab is much different than with the load on the approach slab, unless the joints stiffness is so high that the pavement behaves as a continuous strip.

The differences between LT_{approach} and LT_{leave} would be the result of a preferent inclination of the induced joint crack (Figure 13). Moreover, the predominant condition of joint faces rotated upward reduces the interlockings to the compressed lower edges; therefore it can be anticipated that LT_{approach} and LT_{leave} will converge to a common residual value after the complete breakage of the compressed edges.

Some pavements constructed under cold and humid ambient conditions present a lower joint blockage temperature, which cause their joints to remain closed, and consequently, they have a high load transfer. Blowups are not common in Chilean pavements.

To evaluate internal stresses of pavement slabs, a mechanistic approach is used in which three kinds of joint stiffnesses are considered to take into account the effects of shear forces and moments developed at joints, as well as compressions built up by the slabs' moisture and temperature.

Followup of the load transfer becomes very complicated in practice because it must always be evaluated at equal thermal and moisture conditions and with load positions far from the joint to avoid the effect of skewing.

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