FAULTING EVOLUTION IN UNDOWELED PCC PAVEMENTS WITH SLABS CURLED UPWARDS

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The evolution of faultings in the Chilean in-service undoweled JPCP, after 3½ years of measurements, is presented. A systematic buildup of faultings was observed in Winter in all new pavements up to 10 years old, followed by a decrease during the dry seasons, which is attributed to an accumulation of sandy fines under the approach slab edges, rather than to erosion under the leave edges. In general, the magnitude of faultings in Chile's PCC paved network, is of slight to moderate severity (<4 mm); while imperceptible (<2 mm) in old pavements built on granular subbases. In new pavements, rigid cement treated bases seem to have been of no benefit by opening a slab-base interface under the uplifted edges, thus creating one basic condition for pumping. Influence of thermal conditions (joint openings) and rainfall (infiltrated water) seem to counteract themselves through out the country, making no territorial difference as regards to faulting development. Faulting evolution is presented as a function of pavement age, in absence of traffic data which was not available.

Introduction

The development of faulting at transverse joints of PCC pavements has been of major concern among specialists, since it greatly affects the user's comfort or serviceability, thus increasing the operational cost of ground transportation. Slabs faulting is generally understood to be a consequence of erosion voids under the leave edge of slabs, producing a lack of support that is critical in building up high flexural stresses in the slab concrete; therefore, faulting is also seen as a symptom of structural distress affecting the support integrity. Other studies have suggested that the development of faulting is due to a superposition of such erosion voids and of an accumulation of sandy fines under the approach edge (1); both effects are produced by the pumping of water infiltrated through the many discontinuities of the concrete pavement.

Great efforts to model faulting evolution in undoweled PCC pavements have been made by a research team from the University of Illinois (2,3) taking into consideration a large data-base from several states in U.S.A. (4) and finding significant influence of "some climatic variables (e.g. temperature range which determines joint opening and freezing index) and several mechanistic variables, such as transverse joint opening and slab corner deflection"; also, the erodibility of base/subbase materials is widely reported as an important cause of building up slabs faulting (1,3), with a clear tendency to recommend stiffer un-erodible bases (2,5,6) as well as edge drains and self drainable bases (7).

The purpose of the paper is to show what is being observed systematically in the Chilean in-service PCC pavements as regards to faulting. The results presented herein are part of an extensive research being conducted by the University of Chile under contract of Chilean Highway Administration, with the ultimate objective of modeling the deterioration of the in-service concrete pavements, designed and constructed under general AASHTO guidelines and specifications. This research included the implementation of survey and precise measurement methodologies (8) that are periodically carried out at 21 locations (TS) selected within the PCC paved network, where an important rainfall gradient from North to South and moderate thermal variations are encountered (9,10). At test sections (TS) the yearly rainfall ranges from an average of less than 15 days of heavy rain (TS-1) to more than 120 days (TS-21), as shown in the map of Figure 1 and it is mostly concentrated in Winter. Freezing conditions are not present in the paved network under study.

The pavements under close study were constructed during the last 10 year period, in the course of an extensive rehabilitation program of the highway network. The 0.21-0.25 m thick, plain cement, concrete slabs are resting either on granular bases GR, cement stabilized bases CSB (1 - 2% cement by weight) or cement treated bases CTB (3.5 - 4% cement), built in most cases on old AC or PCC pavements and in other cases on compacted subgrades as detailed in Table 1. CTBs are considered unerodible according to lab test results and to direct field observations (11,12). Nearly half of the 21 test section pavements have edge drains provided.

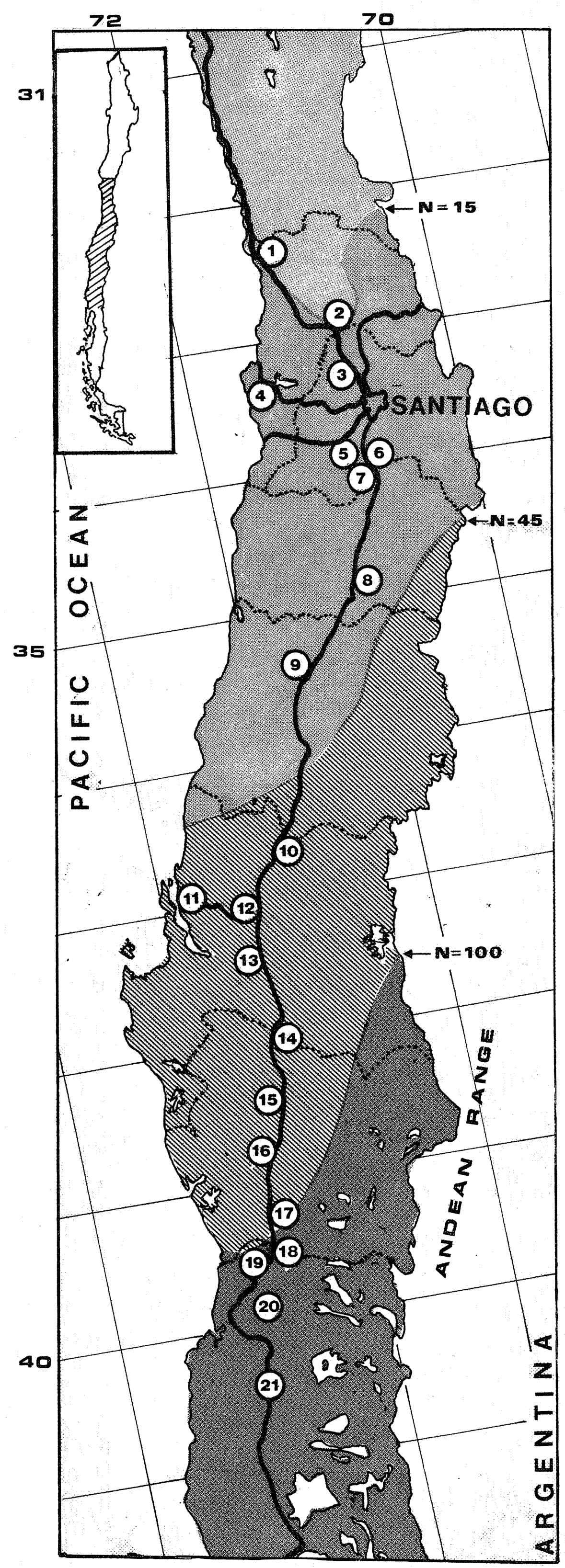


FIGURE 1.- MAP OF TEST SECTIONS AND DAYS N PER YEAR OF HEAVY RAINFALLS.

The shoulders are of compacted granular materials coated with an asphalt chip sealing.

Considering that the pavements under research are rather new, some old pavements still in service were surveyed in the rainy South between latitude 34° and 42° with the aim of covering a larger period of faultings evolution. As discussed later on in this paper, the behaviour of the old surviving pavements greatly differs from the new generation, at least as faulting and pumping effects are concerned. It must be pointed out that these old pavements come from different design and construction practices, as regards to the use of only granular subbases, smaller thicknesses (0.18-0.20 m) and orthogonal undoweled joints, spaced every 6-8 m; curing was by way of impounding or plastic sheetings, for long periods before the traffic of medium weight was allowed to travel on the pavement.

Due to a lack of reliable traffic data, necessary to estimate some equivalent single axle loads, in this paper the evolution of faultings is related only to pavement age, which to some extent mix pavements of different accumulated loadings, but still is considered worthy since most pavements belong to the Pan-American Highway (Chile 5) where the heaviest traffic is concentrated.

TABLE 1. STRUCTURAL CHARACTERISTICS OF TEST SECTIONS

Test Section N°	Season 'Year of Construction	Slab Thickness (m)	Joint Spacing (m)	Edge Drain	Base Type	Sub Base	Sub Grade (USCS)	Water T. Depth (m)
01	Spr'83	0.23	3.7 - 4.6	Y	CTB	AC*	ML	---
02	Spr'81	0.23	4.5 - 5.4	N	CTB	PCC*	CL	---
03	Win'84	0.24	3.4 - 3.6	Y	CSB	PCC	CH	3.4
04	Sum'85	0.26	3.4 - 3.6	Y	CSB	GRM	SM	3.0
05	Spr'75	0.22	3.4 - 5.4	N	GRB	GRM	GC	---
06	Aut'83	0.24	4.2 - 4.6	N	GRB	AC	SP	---
07	Aut'83	0.25	3.6 - 4.6	N	GRB	PCC	GP	---
08	Sum'83	0.23	3.7 - 4.3	N	CTB	PCC	SM	---
09	Aut'83	0.23	3.7 - 4.6	Y	CTB	AC	SM	---
10	Aut'82	0.21	4.5 - 4.6	N	GRB	PCC	GP	2.0
11	Spr'84	0.23	3.5	Y	CTB	AC	ML	---
12	Aut'84	0.22	3.5 - 3.6	Y	CSB	PCC	SC	2.6
13	Win'82	0.21	4.4 - 4.6	N	CTB	PCC	SP	2.5
14	Aut'79	0.21	4.3 - 4.8	N	CTB	PCC	SM	---
15	Aut'84	0.23	4.0	Y	CSB	PCC	ML	---
16	Aut'81	0.21	4.4 - 4.6	N	CTB	PCC	CL	---
17	Aut'83	0.22	4.5	Y	GRB	GRM	GM	3.0
18	Spr'84	0.22	3.8 - 4.3	Y	CTB	GRM	CL	---
19	Aut'83	0.23	4.4 - 5.0	N	CTB	PCC	ML	---
20	Spr'83	0.23	4.3 - 4.6	N	GRB	GRM	GM	2.0
21	Sum'83	0.22	4.5	N	CTB	PCC	ML	1.5

*Old "AC" or "PCC" pavements overlayed with "PCC".

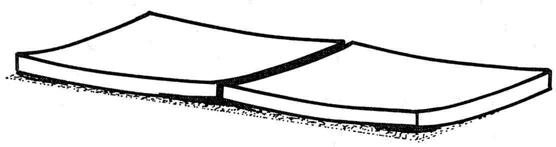


FIGURE 2.- SLABS CURLED UPWARDS BY MOISTURE AND THERMAL GRADIENTS.

Upward Curlings in Chile's New Pavements

As discussed in another paper (13), one of the main characteristics of behaviour in Chile's new pavements is the existence of an upward curling of slabs, that prevails in all sections under study (Figure 2). This curling has been found to be composed of:

- a **"permanent"** component coming from first hours after construction,
- an **"hydric"** component of seasonal variation, and
- a **"thermal"** component which is modified by daily temperature variations.

At any given day the **"permanent"** and the **"hydric"** components are coupled, being very difficult to evaluate separately because reliable moisture data through the concrete thickness was not available. Its existence can be inferred by the joints opening variation through the year, when the slabs moisture changes from a fairly saturated state, after several accumulated Winter rains, to a dry surface and residually moist bottom which is reached by the end of Autumn. Practical consequences of this residual differential moisture are larger degrees of upward curling of slabs while the joints keep most open, imposing unfavorable boundary conditions of partial support and small load transfer (14). According to precise measurements of the slabs corners displacements, the overall upward curling prevails most of the time, either in Summer or in Winter, and becomes evident by the perceptible rocking of the slabs under the early morning traffic, when the slabs are coolest at the surface. In time, the condition of partial support is causing premature cracking in some new pavements, starting at slab edges and from the surface downwards (15).

Looking at the performance of the old surviving pavements, the **"permanent"** component of the curling seems to be missing and most important, the rather soft foundation of slabs on granular subbases would be providing a better support to the concave curled slabs produced by the hydric and thermal gradients.

Results Of Relative Faultings Measurement

After 3½ years of periodic monitoring of Chile's new pavements, starting in 1985, precise measurements of slab faulting conducted by means of the instrumentation depicted in Figure 3, disclose the evolution shown in Figure 4 for three typical test sections. From the plot of the relative faultings at the outer extreme of transverse joints, a positive trend is noticeable, but with systematic increments in Winter followed by a decrease during the Summer until the early Autumn. A similar trend is observed at the middle point of 3 consecutive joints, indicating a relative rotation displacement of the slabs around a longitudinal axis. This behaviour is attributed to an accumulation of sandy fines under the approach slabs edges, rather than to erosion under the leave edges.

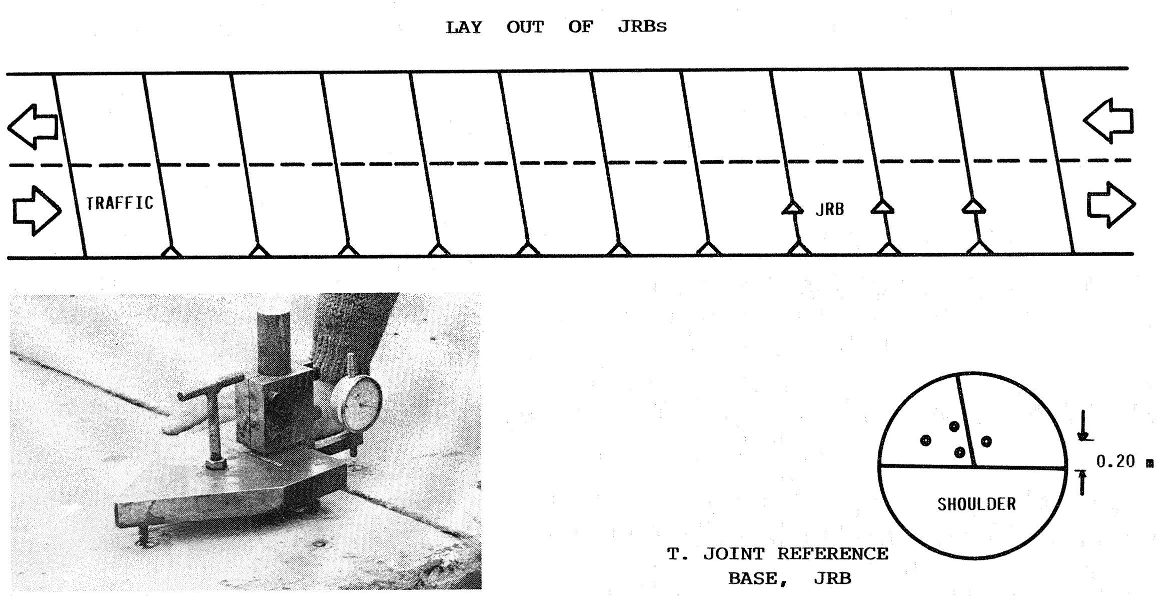


FIGURE 3.- INSTRUMENTATION DEVICE USED FOR THE MEASUREMENT OF FAULTING ($\pm$ 0.1 mm)

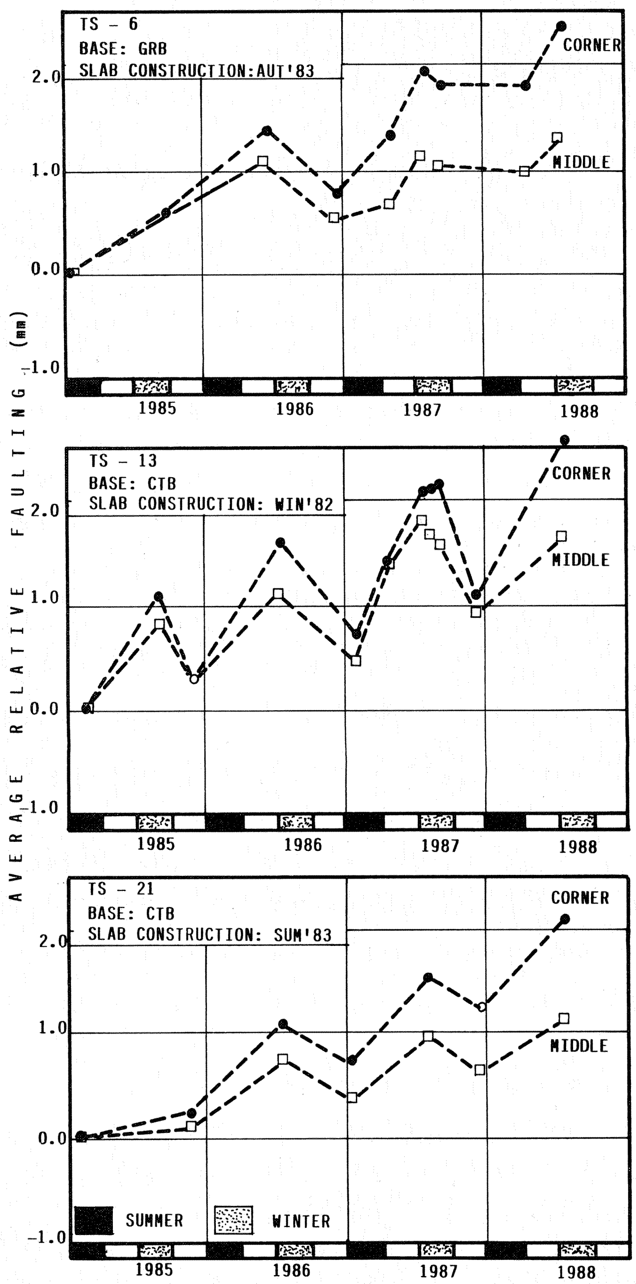


FIGURE 4.- AVERAGE FAULTINGS RELATIVE TO AN EARLY 1985 REFERENTIAL STATE.

To explain this statement, a recall must be made of the upward curlings already mentioned. In fact, considering that the development of faulting is possible by the concurrence of:

- an open interface between the base and the slab edge,
- water filling that space,
- deflections of the slab edges caused by traffic loads, and
- fines available from the base and/or from the shoulder;

faulting across transverse joints would be the result of erosion, producing a significant void or cavity under the leave edge, and/or of accumulation of fines under the approach edge through a wellknown mechanism of pumping out and suction, as the slab is suddenly loaded and unloaded by the passing wheels (1,16). As it has been observed, the transportation of fines may also be produced, though to a less extent by a pumping of air, whose most visible result is a blowing out of shoulder fines during the dry Summer.

Measurements of slab displacements by temperature and deflections by traffic loads prove that the slab-base interface is open during the most part of a thermal daily cycle as shown in Figure 5 for a typical pavement. These data are part of a bank obtained with precise instrumentation that was described on another paper (13), consisting essentially in an A/D measurement system that uses LVDT's connected to deep reference bases (DRB) and thermal sensors (8).

Figure 5 presents the simultaneous uplift and peak deflections of two outer corners of adjacent slabs (DRB1 and DRB2), as well as the thermal changes observed through out a continuous cycle of 24 hours. This cyclic uplifting of corners, shown with ordinates increasing upwards and referred to the smallest value of the day, have a maximum during early morning when the slabs are coolest; so do the deflections caused by a slow moving axle load of 110 KN, shown with downwards ordinates on the same graphs. It is important to note that the corners remain uplifted most of the day, with a strong warming up of the slab surface (positive gradient) being necessary to reverse the curling and get the edge supported on the base. The corner support condition is restricted only to the hot hours of a sunny day, remaining unsupported from the late afternoon until late morning, through the night; this condition can be generalized to every cloudy day including, of course, the whole Winter. The duration of the uplifts through out a day cycle are summarized in Table 2, together with an indication of the uplift magnitude, which in general, may be different for the two adjacent corners. Since this difference can affect the faulting readings, all measurements were made during favorable hours.

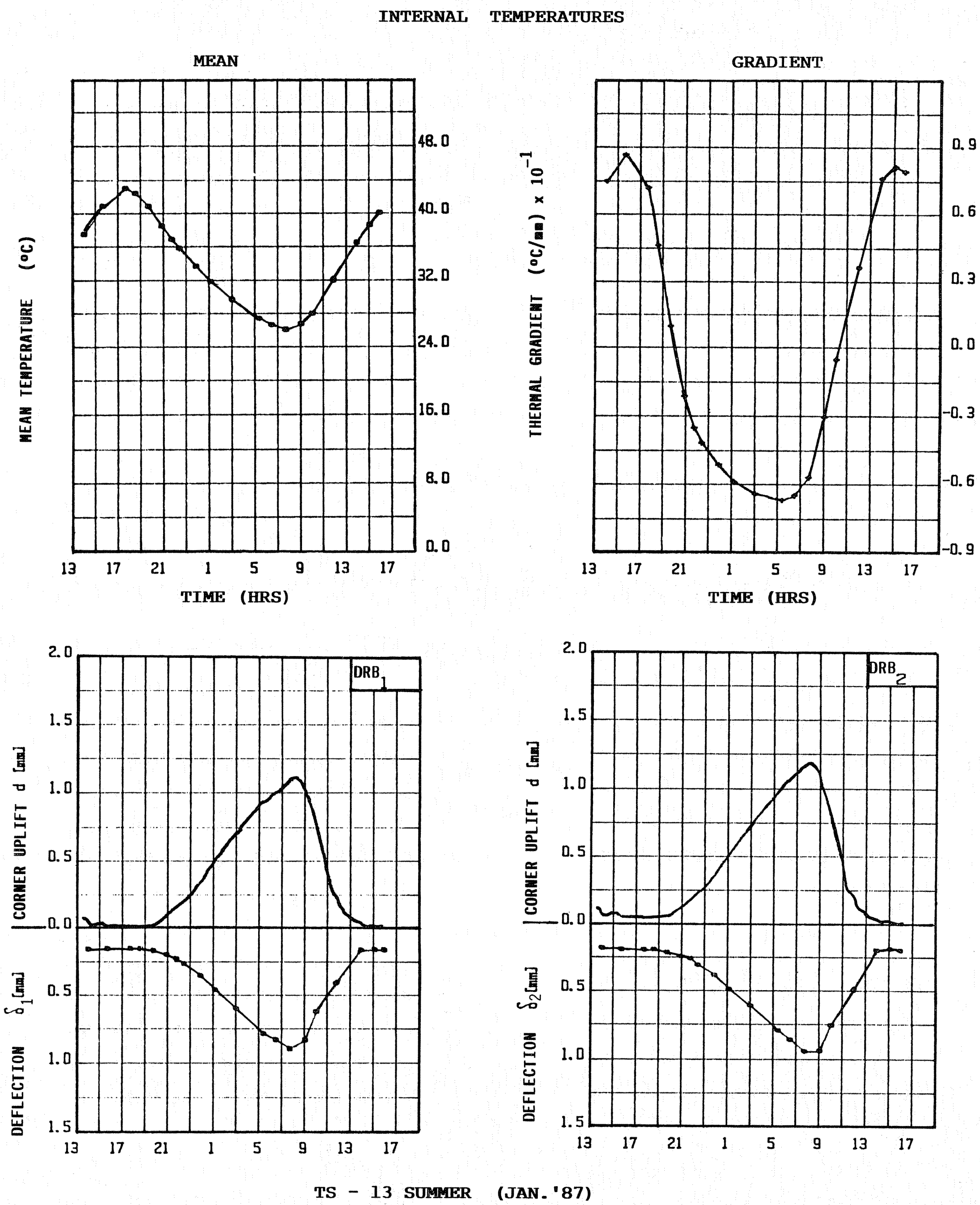


FIGURE 5.- CONTINUOUS SLAB DISPLACEMENTS AND LOAD DEFLECTIONS DURING A SUMMER DAY CYCLE, FOR A 110 KN MOVING LOAD.

TABLE 2. MAXIMUM UPLIFT OF CORNERS

TS Nº	Slab Length (m) L_1	L_2	Slab Construc. Season	Measure Season	Thermal Cond. Mean T. °C	Grad. °C/mm	Max. Uplift of Corners* (mm) DRB 1	DRB 2	Accumulated hours
6	4.64	4.57	Aut.'83	Aut.'86	7.0	-0.03	0.59	0.52	24
				Sum.'86	25.5	-0.04	0.63	0.65	14
				Aut.'88	16.0	-0.03	1.28	0.85	24
13	4.52	4.62	Win.'82	Win.'86	9.3	-0.02	0.18	0.36	20
				Sum.'87	26.0	-0.06	1.12	1.22	16
				Win.'87	7.5	-0.01	0.25	0.60	24
				Spr.'87	24.0	-0.03	0.26	0.25	24
21	4.50	4.48	Sum.'83	Win.'86	3.2	-0.04	0.19	0.19	16
				Sum.'87	24.0	-0.03	0.80	1.21	14
				Win.'87	11.5	-0.01	0.05	0.05	24
				Spr.'87	16.0	-0.02	0.70	0.75	24

*Winter data are relative to the day minimum and do not represent the total corner uplift.

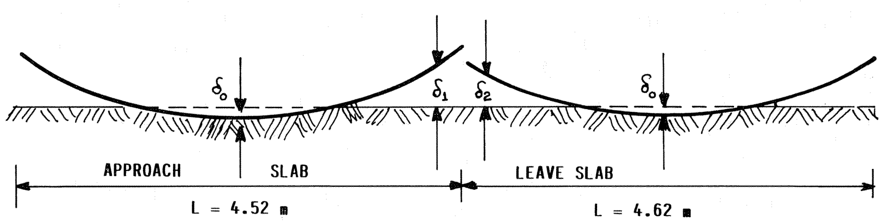
In Figure 6, the peak deflections at points DBR1 and DRB2 are plotted against corner uplifts for three complete 24-hour thermal cycles, considered representative of the general behaviour of all 21 test section pavements. For each load the relationship is clearly linear in both corners and with similar slopes ($m < 1$), and such that the total deflection may be expressed as:

$$\delta = \delta o + md \text{ ----------------- } (1)$$

δo : representing the contribution of the elastic deformation of the support under the central zone of the slabs, and

md : the elastic deflection of a cantilever piece of slab.

For the maximum legal 110 KN load the elastic deflection $\delta - \delta_o$ has a magnitude less than the uplift **d**, such that the edges do not get in full contact with the base, especially with rigid CTB's (13). As a consequence, a void under the leave edge should not contribute to faulting because of the high rigidity of slabs.



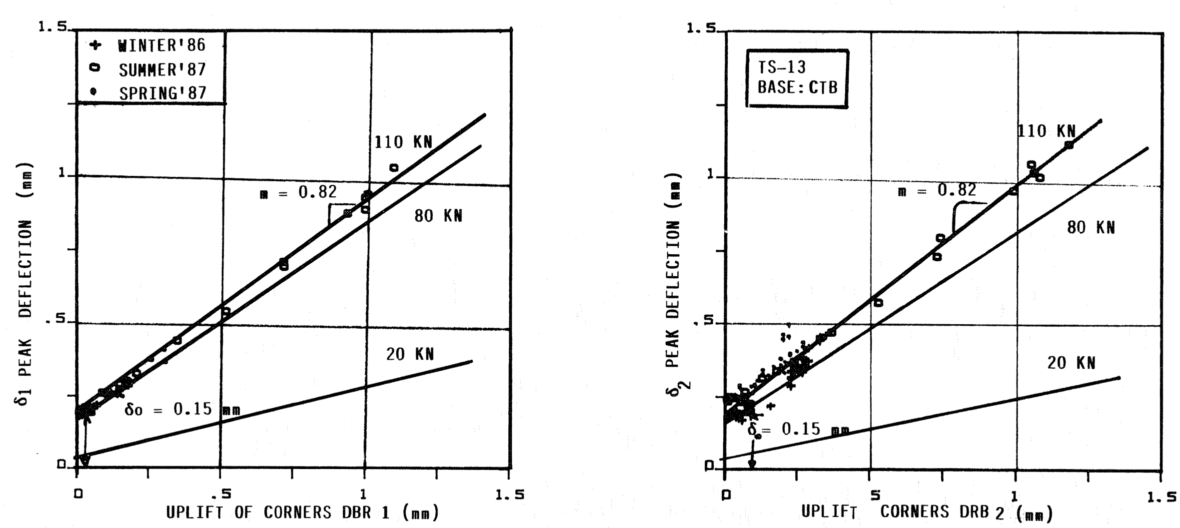


FIGURE 6.- SLAB CORNERS DISPLACEMENTS AND MAXIMUM DEFLECTIONS DURING WINTER & SUMMER DAY CYCLES.

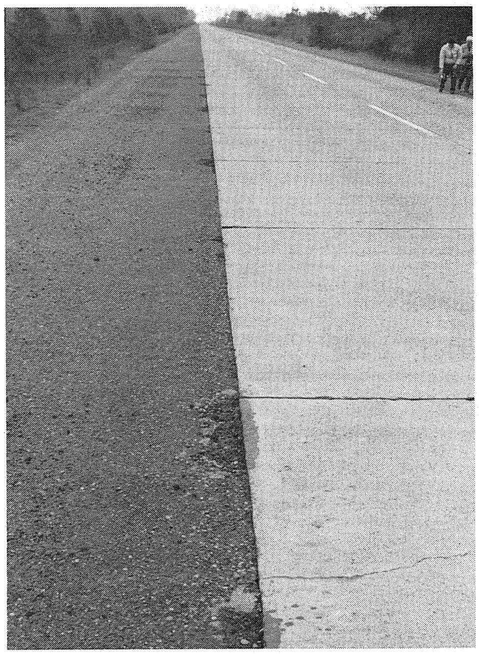


FIGURE 7.- SYSTEMATIC EROSIONS AT LEAVE EDGE CORNERS AND VISIBLE FAULTINGS.

On the other hand, the suction produced by the elastic recovery of slab deflections, after the wheels have passed, is more effective in accumulating fines underneath the approach side than in the leave side, in an action that continues during the whole Winter, or as long as the slab-base interface is full or water. However, in Chile the rainfall is concentrated mostly in Winter, with long periods of drought or light rains (less than 5 mm/day) during the Summer, from late Spring until late Autumn, especially in the central regions around Santiago, and there are chances for the fines to get dry and blown by the air being pumped by the traffic loads, thus producing a redistribution and a flattening up of the accumulated heap of fines under the approach edge. The results of this action is a decrease in the faulting during the dry months, as it is shown by the sawtooth shape of the evolution curves in Figure 4.

Another sign of pumping is visible by holes in the shoulders, close to the slabs outer edge, as illustrated in Figures 7,8,9. Erosion starts systematically at leave corners, destroying the asphalt cover, to proceed later towards the approach side at more advanced states of distress. With respect to the magnitude of shoulder holes, a high dependence on the erosion susceptibility of the shoulder fill material has been observed; being very important in sandy fills, which is the case of TS-13 (15-17% passing through sieve #60 ASTM) and almost negligible in coarse granular, as in TS-06 (less than 10% passing sieve #60). The complete particle size distribution of all shoulder materials is well graded and low permeabilities can be expected when they are compacted to a high degree and therefore very susceptible to trap the rain water.

FIGURE 8.- EVIDENCE OF PUMPING AND EROSION AT LEAVE EDGE CORNER IN A 9 - 10 YEAR OLD PAVEMENT.

FIGURE 9.- NEW GENERATION PAVEMENT SHOWING SIGNIFICANT FAULTING AND EROSION HOLE IN FRONT OF LEAVE EDGE CORNER.

Absolute Faultings

In order to quantify the absolute faultings in all concrete pavements, a simple apparatus was devised (Figure 10), that needs no fix reference bases but yields a precision estimated in ± 0.25 mm. Individual readings from joint to joint show typically a high variability around the average that is beyond the precision range of the measurement and independent of the joint spacing.

Looking at the 21 test sections all together, plus other PCC pavements not included in the original research, Figure 11 presents the absolute faultings, as an average of 30 consecutive joints, measured last Winter'88 and plotted against the pavement age. Different trends can be identified between the old and the new generation pavements built after 1977, which now accumulate at most 10-11 years in service. Old pavements, built on granular subbases, have developed a faulting magnitude of slight severity according to ACI ratings (17), which seem to be stabilized around 2 mm and it is barely noticeable by the user. In these pavements the joints turn out to be more perceptible by the ridge of asphaltic resealing rather than to the stepping (Figure 12).

In the new generation pavements, absolute faultings are increasing with age, in a S-shape tendency that seems to be approaching an equilibrium magnitude somewhere in the range of moderate severity when the pavement reaches its design life period of 20 years. According to the cracking

FIGURE 10.- APPARATUS USED FOR THE MEASUREMENTS OF ABSOLUTE FAULTINGS.

of the slabs that is being observed in some new pavements, attributed to the unfavorable boundary condition or support (11), the authors think that a generalized future cracking, producing a natural subdivision of the slabs, will tend to reduce or at least stabilize the faultings development. The **"Summer effect"** reducing the winter build up of faultings, further support that hypothesis.

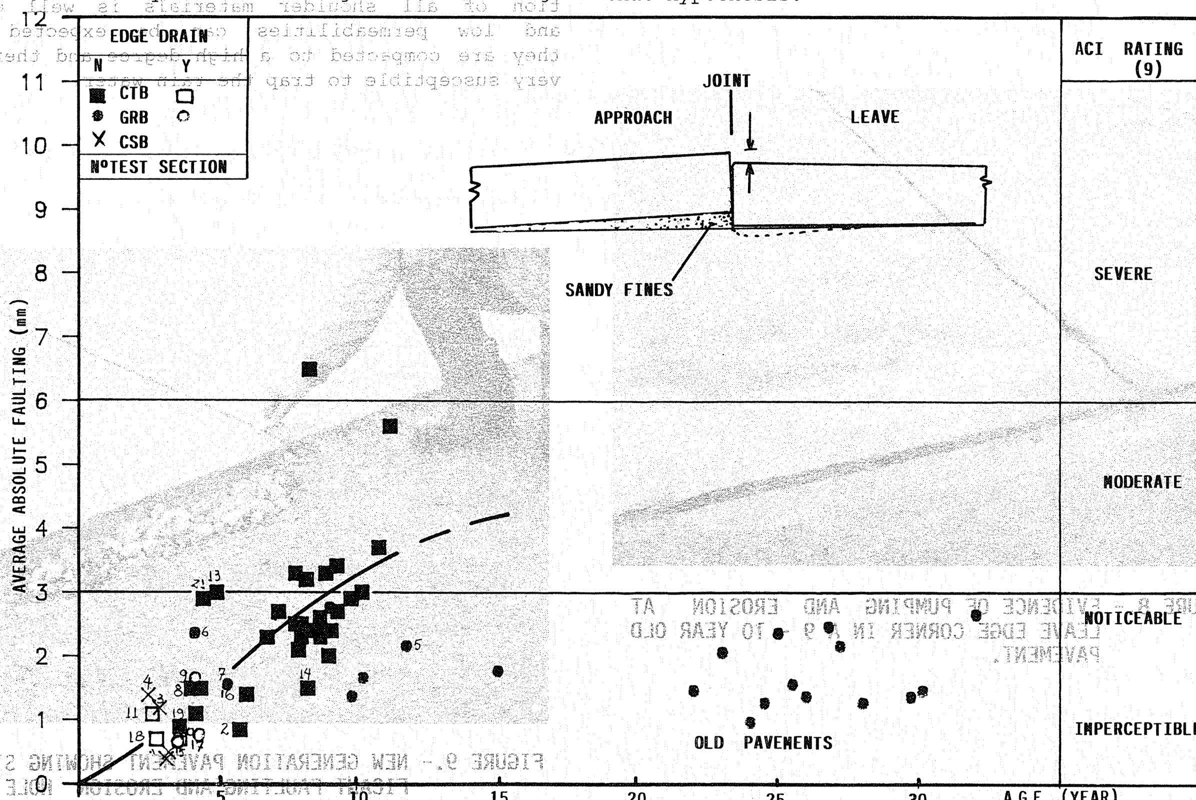


FIGURE 11.- PRESENT STATE OF FAULTINGS IN THE CHILE'S PCC PAVED NETWORK (JUL - AUG. 1988).

One of the design features of the new pavements, making an important difference from the old ones, is the use of rigid and impermeable CTBs that seem to be of no good as the faulting development is concerned. In fact, the CTB with 4-4.5% cement is considered non-erodible and unable to provide sandy fines; but at the same time it is impermeable, therefore restricting the water flow to be only horizontal as compared with the granular subbases that permit some downward flow by its intrinsic permeability. On the other hand, cement treated bases under curled slabs provide a rigid support, restricted to its central part, that increases the volume of water to be pumped from the CTB edge slab interface. From these points of view, cement treated bases would develop faulting more easily than granular subbases.

On the other hand, faulting development is said to be related to joint opening due to a load transfer resting on aggregate interlocking (2,3), thus affecting the magnitude of deflections. In order to investigate that variable, Figure 13 shows that maximum joint opening, representative of mean temperature conditions in the Winter, decreases from North to South according to a sharp relationship (15), indicating that the pavements in the North should fault more than in the South. However, rainfall tendency is just the opposite as shown by Figure 1; therefore, some sort of compensation between joint openings and rainfall is produced in the particular case of Chile's climate that turn the faultings independent of joint spacing, and consequently of joint openings, as shown by the apparently random distribution of the points plotted in Figure 14, representing pavements of the new generation and with different types of base.

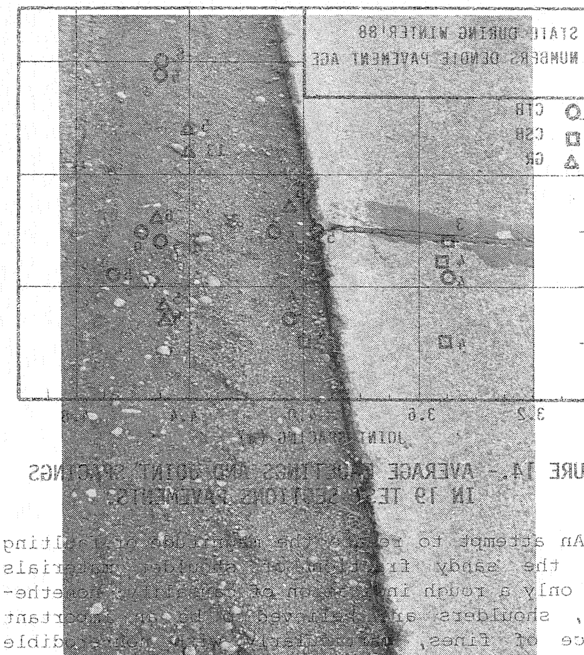


FIGURE 12.- OLD GENERATION PAVEMENT SHOWING NO FAULTING AND UNDAMAGED GRANULAR SHOULDER

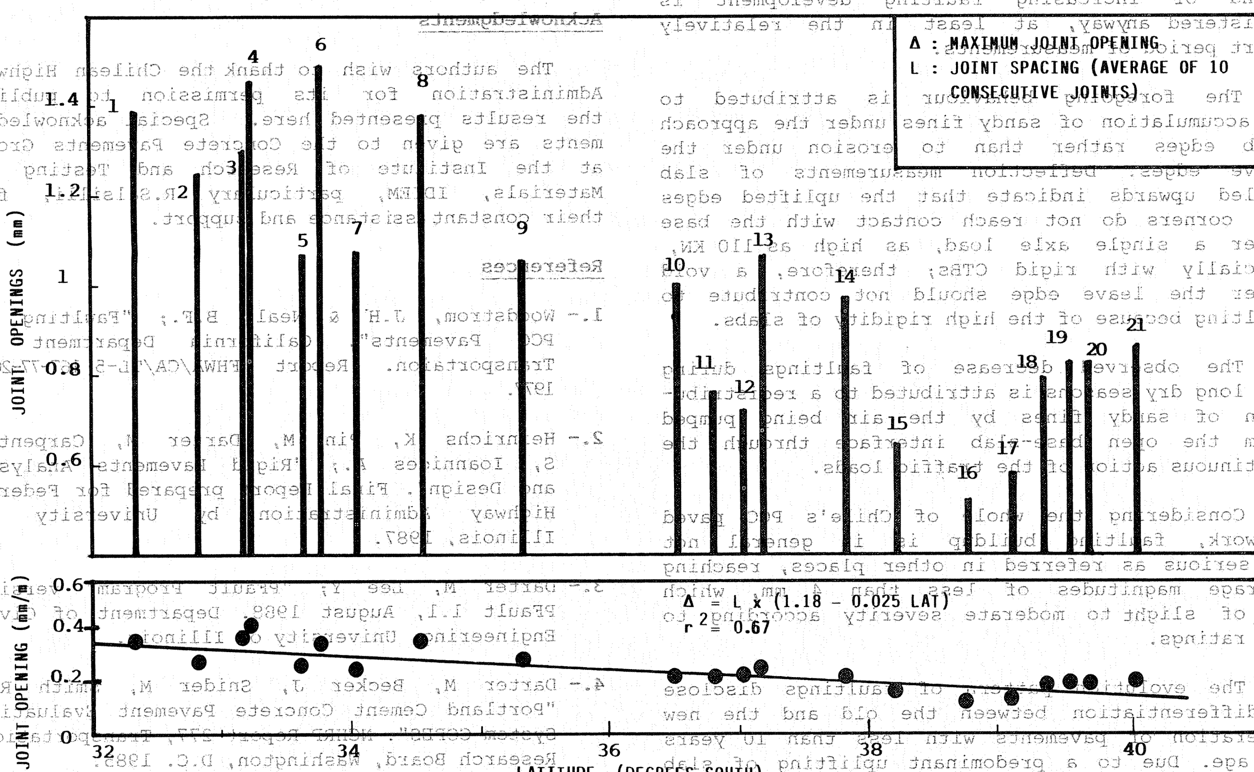


FIGURE 13.- MAXIMUM JOINTS OPENINGS OF TEST SECTIONS PAVEMENT AND ITS RELATIONSHIP WITH LATITUDE.

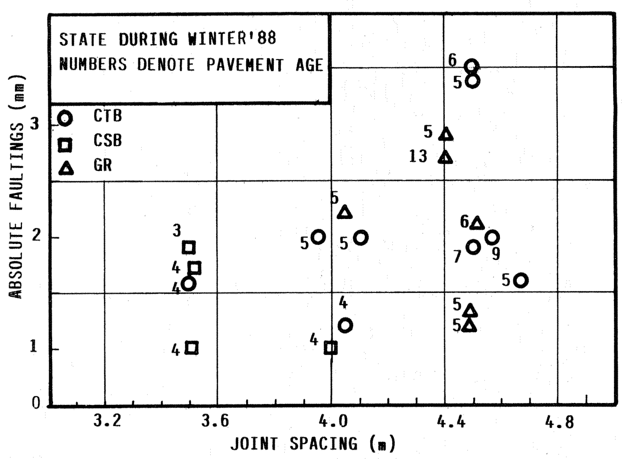


FIGURE 14.- AVERAGE FAULTINGS AND JOINT SPACINGS IN 19 TEST SECTIONS PAVEMENTS.

An attempt to relate the magnitude of faulting with the sandy fraction of shoulder materials gave only a rough indication of causality; nonetheless, shoulders are believed to be an important source of fines, particularly with non-erodible cement treated bases.

Conclusions

After 3½ years of precise measurements conducted in pavements with upward curled slabs, systematic buildup of faultings was observed in Winter in all new pavements up to 10 years old, followed by a decrease during the dry seasons. A positive trend of increasing faulting development is registered anyway, at least in the relatively short period of measurements.

The foregoing behaviour is attributed to an accumulation of sandy fines under the approach slab edges rather than to erosion under the leave edges. Deflection measurements of slab curled upwards indicate that the uplifted edges and corners do not reach contact with the base under a single axle load, as high as 110 KN, specially with rigid CTBs; therefore, a void under the leave edge should not contribute to faulting because of the high rigidity of slabs.

The observed decrease of faultings during the long dry seasons is attributed to a redistribution of sandy fines by the air being pumped from the open base-slab interface through the continuous action of the traffic loads.

Considering the whole of Chile's PCC paved network, faulting buildup is in general not as serious as referred in other places, reaching average magnitudes of less than 4 mm, which is of slight to moderate severity according to ACI ratings.

The evolution pattern of faultings disclose a differentiation between the old and the new generation of pavements with less than 10 years of age. Due to a predominant uplifting of slab edges and corners, the new pavements are developing a significant faulting between 4-4.5 m long slabs, that seem to be approaching a stabilized moderate severity before getting subdivided by transversal cracks. This crack pattern is typical of the observed upward curled slabs on rigid CTBs. Some older pavements on granular subbases have developed imperceptible to barely noticeable faultings, even after 20 years or more, without cracking; which obviously is a practical proof of good support under every point of the slabs.

Regarding a possible influence of climate on slab faultings, no definite trend with latitude has been found, as could be expected by rainfall increasing North to South during a normal year, from less than 200 mm in TS-1 to more than 1250 mm in TS-21 or 1980 mm in latitude 42°S. This is attributed to some sort of compensation through the joint openings, that tend to decrease in the same direction due to colder mean temperatures.

As for maintenance options when the faultings exceed some threshold values, the most effective action for these pavements appear to be the cut-off of fines mobilization from the shoulder and the installation of maintainable edge drains to avoid the water trap. Drains properly installed will serve both purposes.

In pavements with upward curled slabs, the shoulder interface keeps virtually open due to the slabs deflections and rocking, allowing the rain water to flow into the pavement infrastructure in spite of a good maintenance policy of joint sealing.

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