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Effects of temperature changes on load transfer in plain concrete pavement joints

Efeito das variações de temperatura na transferência de cargas em juntas de pavimentos de concreto

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Abstract

A field investigation of load-induced deflections using a FWD device allowed evaluating the joint behavior of plain jointed concrete pavements regarding its load transfer efficiency (LTE) at joints. Such parameter, at non dowelled joints, present a large variation along day hours as well as along the seasons (winter and summer); while dowelled joints disclosed little variation for LTE with values ranging from 90 to 100%, non dowelled joints have reduced transfer efficiency between 50% (winter) to 60% (summer). Using FEM-based software it was allowed to estimate very similar values, matching the field data, confirming the requirements for considering LTE behavior at joints during structural analysis and design of concrete pavements.

Keywords: joints; plain concrete pavements; load transfer.

Resumo

Medidas de deflexões com o falling weight deflectometer permitiram a avaliação do comportamento de juntas em pavimentos de concreto simples do ponto de vista de sua eficiência de transferência de cargas (LTE). As investigações mostraram importantes variações nesse parâmetro, quando não há dispositivos de transferência de cargas, entre horários de dias bem como entre estações climáticas distintas (inverno e verão); enquanto que juntas com barras de transferência apresentam, pouca variação nesse parâmetro e encontrando-se em geral entre 90 e 100% de capacidade de transferência, quando há quedas de temperatura, as juntas sem barras chegam a apresentar capacidade de transferência reduzida para 50% no inverno e para 60% no verão. Valores estimados de transferência de carga com um programa de elementos finitos permitiram confirmar a necessidade de tratamento teórico do problema em fases de análise estrutural e projetos de pavimentos de concreto com juntas.

Palavras-chave: juntas; pavimentos de concreto simples; transferência de carga.

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1. Introduction

Almost all types of concrete pavement in slab systems have joints with the exception of pavements with continuous reinforcement, whose joints, when occur, are only constructive ones. In addition, shrinkage cracks can be seen as joints. The joints are cross-sectional and longitudinal and in both cases, load transfer occur between side or successive slabs when a load is approaching to this joint, whether or not there is effort transmission element. There may be load transfer due to dowel bars; however, in the absence of that, yet load transfer occurs by interlock effect between aggregates in particular when it is a contraction joint. This friction mechanism and shear in concrete adjacent vertical faces may also occur either in construction joints or between pre-fabricated slabs in equal or lesser scale (Figure [1]).

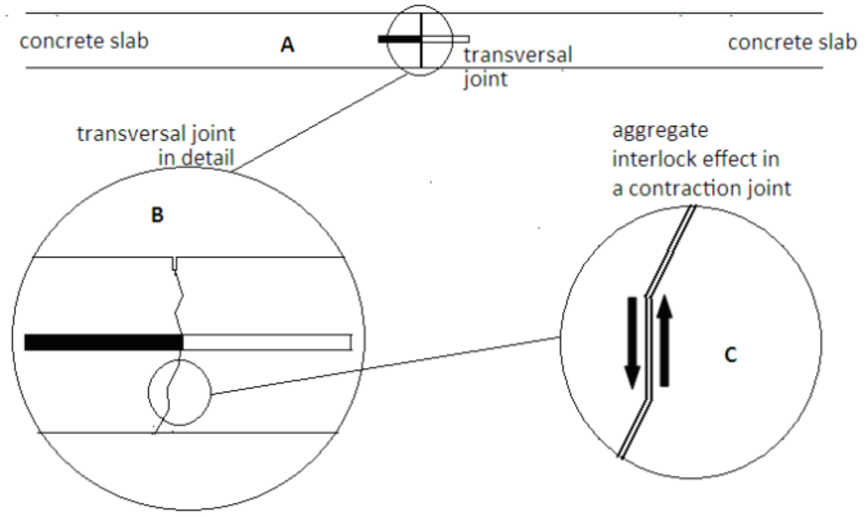
The load transfer effect consideration in concrete pavement joints is essential in design and structural analysis whether new or in old floor restoration. Through these effects is that horizontal stresses imposed in structural system, next to these joints, can be drastically reduced, which is a positive fact in determining project resistance for concrete, reinforcement rates, slab thickness and structural reinforcements. The smaller or larger load transfer efficiency is dependent on the system temperature (joint opening), the modulus of subgrade reaction and the joint type (contraction with or without load transfer, construction or expansion bars). The effective measure of load transfer effects can be done, experimentally, by using two techniques. In the first one, the pavement is instrumented with *strain gages* and load cells that allow to measure deformations in concrete and pressure on lower layers by approaching a moving load to a joint; however, this procedure is expensive, which will be take into account as an alternative technique. The vertical deformations can be measured on the concrete surface (deflections), in two opposite positions, orthogonally and also away from the joint, when the load is applied in one of positions [1]. With performing load transfer, the discharged slab move d_2 in a more or less sympathetic way to the charged slab d_1 moving, thus allowing the determination of an arbitrarily named parameter for the load transfer efficiency (from English load transfer efficiency – LTE), according to equation [1]:

$$LTE = \frac{\delta_2}{\delta_1} \times 100 [\%] \qquad (1)$$

By equation [1], if the charge transfer is null, the deflection in the discharged slab is also null, in which case only the charged slab undergoes deformation. When LTE reaches 100%, the load transfer is the highest, such that the vertical deformations on both slabs must be identical. When one consider that the structure response in the joint should not be dependent only on the previously mentioned transfer elements, even though the joints were completely without contact, throughout the slab depth, any transfer would happen through lower layers [2] and assuming that LTE extreme values would require a great distance between the joint faces, which would be more palpable in the case of expansion joints.

Based on the exposed concepts, it is to be expected that LTE affects the performance of concrete pavements as well as seasonal changes over time. According to the *American Concrete Pavement Association* [3], the LTE value must not be less than 75% for a provided load transfer, by a joint, to be considered appropriated. Concrete pavement calculation methods that are current adopted in the country such as the one in São Paulo City Hall [4], an official method, and according to the *Portland Cement Association* guideline [5], a non-official method, they do not consider explicitly the LTE value and its seasonal nuances. Thus, determined stresses values in the design can distance from the field reality, where LTE varies with climatic conditions to which pavements are exposed. In the absence of such studies in wet tropical climate, it is essential that some research be undertaken to establish load transfer pat-

Figure 1 – Dowel and aggregate interlock



terns in transverse joints of plain concrete pavements. Work of this nature will enable updating and improvement of sizing methods for LTE changes consideration over the project service-life, which means admitting differentiated structural answers of pavements over time, which is an inexorable fact. It was the goal in this article to describe experiments that were done by characterizing LTE values in different climatic conditions, taking into account the effect of cemented and granular bases in plain concrete pavements at contraction joints, with and without dowel bars.

2. Main aspects on load transfer

The first record of dowel bar is from 1918, used in plain concrete pavement, in *Newport News*, Virginia [3]. Friberg [6] indicated that dowel bars should be of plain steel with 600 mm length and circular diameter of 19 or 22 mm on most highways, and should be spaced 300-500 mm; besides that, half bar should be greasy not to adhere to the concrete. However, until 1970s and 1980s, many roads and corridors were built without dowel bars in many countries, including the USA, but this was unusual in Europe; as a consequence of this technique, the faulting in transverse joints with subsequent uneven edges break (faulted joints), were generally observed, damaging the users' comfort. Khazanovich wrote about it [7]: "M*any concrete pavements performance with joints have not been historically interpreted by its structural capacity, but rather by its joint system... Mediocre values of load transfer efficiency lead to occurrence of longitudinal and corner cracks, in addition to expressive deflection in the joints. These defects may lead to the presence of irregularity and poor bearing conditions."*

It was found in a poll conducted in North America [7] that only between the 1970s and 1990s almost the totality of States and provinces were required to build concrete pavements with dowel bars. It is noted that, even in the USA, the understanding process of dowel bars in joints to improve the long-term performance of concrete pavements date back to around two or three decades ago. It is clear then the existing technical dichotomy for traditional users of concrete pavements such as Germany, Austria and Switzerland, where since the 1930s the use of dowel bars on highways was not dispensed [8]. In a recent study in the laboratory [9] tests were performed to assess the structural behavior of transverse joints in simple concrete slabs with reduced dimensions in relation to conventional pavements; the concrete slab thickness ranged as well as the imposed loading, in addition to several devices of load transfer being tested. The results allowed noting that the BT use in concrete pavements makes the load transfer significantly higher than in the case of load transfer device absence. Of course, this affects the concrete pavement performance in operation.

2.1 Load Transfer Measures in Joints

Khazanovich and Gottif [10] declare that load transfer measures in joints from researches of *Strategic Highway Research Program (SHRP)* pointed out that LTE values range as smaller than 20% and also near 100%. The measures were implemented also in slab cracks, trying to understand the damage effects on the same slab by means of checked load transfer. They concluded that approximately 10% of the joints had LTE below 50% while the vast majority of cracks resulted in calculated LTE above 85%.

In order to investigate the soil resistance influence of foundation in load transfer efficiency and durability, Colley and Humphrey [11] used three subgrade types in their study: clay, gravel and a cement-treated base. With an opening in the joint of 0, 89 mm and on the clay subgrade, comparing the two different thicknesses slabs (180 and 280 mm), the load transfer efficiency was 5% for the thinner and 29% for the thicker slab. Clearly, the thicker slab rigidity contributed to the pavement resistance on this subgrade type. Concerning to granular basis, the efficiency increased for 9% and 50% respectively. And it increased even more on cement-treated base. They also concluded that the higher the joints' opening, the lower system load transfer efficiency.

Vandenbossche [12] found that the load transfer efficiency in concrete pavement slabs of new plain concrete pavement without BT in the joints may vary between 70 and 100%. LTE in new pavements with BT varies between 80 and 100%. The *Federal Highway Administration* [13] recommends that the concrete pavement restoration, used to prevent future damage, should occur when one of the following conditions is checked: the 3 mm joint scaling or cracking or more; LTE less than 70%; difference between deflection in the loaded slab are greater than 0.25 mm in the unloaded slab; and joint scaling and cracking accumulation above extension of 525 mm/km.

2.2 Temperature and Joint Opening

Shahin [1], based on LTE measurements in plain concrete pavements joints at airports in the U.S., suggests that the joint load transfer can be adjusted according to temperature or time of the day, as the LTE values that occur at the beginning in the morning are lower than those verified at the end of the day due to concrete expansion. The following function with the correction factor (F) is proposed to be held this correction in the LTE value (known only a LTE value makes possible the LTE determination for any time of the day):

$$LTE = \frac{\delta_2}{\delta_1} \times (1 + F) \times 100 [\%] \qquad (2)$$

This correction factor is given graphically for certain periods of pavement measurements. This template indicates an F decrease between 8am and 2pm, and F is null after this period for the 2pm reference time. The LTE determination for the 2pm is performed by the equation [2] based on LTE measurement for any time, determining the correction factor for this measurement time. F values are calibrated based on field measurements of prevailing conditions in USA northeastern (temperate climate).

The concrete temperature, resulting in its expansion or contraction, interferes with the joint opening along the pavement service life. The load transfer efficiency is drastically reduced with the joint opening increase [14]. Thus, the joint opening should be as small as possible, which transfer bars, and in pavements with continuous reinforcement it may be controlled more effectively.

A study to understand the effect of the different concrete pavement characteristics in relation to the joints opening used twelve test sections built in Chillicothe, Ohio, with several slabs' lengths, types of bases, types of dowel bars and joint sawing modes [15]. The pavement had two lanes 3.6 m wide and 230 mm CCP slab thick-

Table 1 – Experimental plain concrete pavement sections at USP

Section	Slab	Length (m)	Slab thickness (mm)	Base type	Base thickness (mm)	Dowels
A	A1	4.00	150	CS	200	In both joints
	A2	5.50	150	CS	200	
	A3	7.50	150	CS	200	
B	B1	4.00	150	RCC	200	In both joints
	B2	5.50	150	RCC	200	
	B3	7.50	150	RCC	200	
C	C1	4.00	250	RCC	100	In both joints
	C2	5.50	250	RCC	100	
	C3	7.50	250	RCC	100	
D	D1	4.00	250	CS	100	In both joints
	D2	5.50	250	CS	100	
	D3	7.50	250	CS	100	
E	E1	5.50	250	CS	100	Only between slabs E1 and E2
	E2	5.50	250	CS	100	
	E3	5.50	250	CS	100	

ness. For both bases were used both granular and stabilized materials with cement. In the study it was observed that the maximum horizontal movement of concrete slabs occurred in the months when the temperature widely varied between day and night, being related to temperature in the concrete with the horizontal displacements in the slabs. The study showed that the maximum movement (opening) occurs in colder months. This is evidence that the LTE at low temperature is lower due to concrete contraction. It was also verified that base type, whether it was granular or stabilized with cement, did not affect the joint opening, which is really important for structural analysis. This is indicative that the base use such as RCC (roller compacted concrete) or CTCS (cement treated crushed stone) would not restrict the slab movement differently from well-graded gravel or other granular bases.

Khazanovich and Gotlif [10] studied data from many road sections within the LTPP/NHCPR program, including joint opening measures at different times of day and seasons, which did not exceed 2 mm, considered all roads' sections.

For Vandenbossche [12], LTE in BT-free joints can decrease more than 50% when the opening is larger than 0, 9 mm. The author indicates that with tests using *falling weight deflectometer* (FWD), LTE values resulted in 50% in the morning and 90% in the afternoon. Greer [16] also obtained results showing change from 16 to 84% in LTE values in slabs without BT as temperature changes between winter and summer weeks. These changes were not significant when there was a load transfer device (BT) in the plain concrete slab joint.

In a Japan survey [17], it was developed a relational model between LTE and the joint opening for pavements with and without BT. The authors noted that in the case of BT presence, the opening has little influence on the LTE value compared to the case of concrete pavements without BT. The LTE value with BT decreased with the joint opening, tending asymptotically the minimum value of 80%. It was also checked that slabs without BT, the LTE value falls linearly because of joint opening, tending to zero for an opening around 4 mm.

Field analysis were done in laboratory under PCA [11] to evaluate the efficiency and durability of load transfer due to the aggregated interlocking in cracked concrete faces. Variables were then considered: the joint opening, foundation resistance, and load level and slab thickness. Two types of aggregates for concrete were used: well-rounded pebble and gravel stone with sharp edges. Regarding the joint opening, which ranged from 0.5 to 2 mm, it was verified that the higher the opening joint, the lower is its efficiency in load transferring.

Poblete *et al.* [18] determined that the maximum difference between joint opening at the top and bottom slab found in a plain concrete pavement in Chile was of 0.15 mm in pavements without BT. Pittman [19] observed that the joint opening width on the surface was statistically equal at the bottom of the crack.

2.3 Effects of reaction system for slab support

Regarding the subgrade reaction modulus (k) effects in the concrete slabs, analytical models like that of Westergaard [20] and numerical, like that of Balbo [21], both using the concept of Winkler foundation, showed that variations of this parameter in concrete slab stresses is very small. However, works as of Spangler [22] based on experimental road clearly show that there are differences between this concept of subgrade reaction when a load is applied on slab edge or center. Shahin [1] in his analysis used the finite element method for load simulation applied in the concrete slab corner, determining LTE values due to subgrade reaction modulus (k) and the maximum deflections obtained in the evaluated slabs, in a backcalculation process. The results gave clear indications that for the same deflection amount, the lower the value of modulus of subgrade reaction (k), the greater the load transfer (higher LTE). In other words, the load transfer descriptor parameters in the joints and in the pattern of support layers springy deformability would work together in defining the deflections imposed by the external loading.

Zollinger [23] presented results of an experiment in plain concrete pavements with different thicknesses of concrete slabs (200 to 360 mm) in order to analyze the joint opening in the concrete slab due to subgrade reaction module. The results indicated that for the same value of subgrade reaction modulus (k), the greater the thickness of the concrete slab, the greater should be the joint opening for the same deflection. These results support the hypothesis that the structural parameters work together and are difficult to individualize in an evaluation, but different value combinations may result in similar effects.

3. Load transfer tests in experimental concrete slabs

The concrete slab's analysis in true greatness, regarding the load transfer in joints, was carried out in the existing experimental plain concrete pavement area at USP campus in São Paulo. The studies' details are presented as follows:

3.1 Deflection Measures in experimental road

The road with experimental plain concrete pavement at USP has five sections with different structural characteristics for the concrete slabs as indicated in Table [1]. The dowel bars are spaced among them by 300 mm; they have a 32 mm diameter (CA-25 Brazilian grade steel pattern) and 400 mm length. The pavement bases are made of plain graded crushed stone (CS) or of roller compacted concrete (RCC), all over an area with very homogeneous clay subgrade soil [24].

Tests with FWD (Figure [2]) were performed as described in Table [2], aiming to include two distinct seasons in São Paulo: winter (mild) and summer. Deflection measurements were made with seven sensors (geophones), one under the load application plate (this plate has 300 mm diameter). The top temperatures and values of thermal differences between top and bottom slab (calculated according to the defined empirical model in the proper experimental road [24]) are presented in Tables [3] and [4]. The applications of load on concrete pavement were performed with three load levels (approximately 47, 74 and 84 kN) to evaluate the effect of loading on the pavement structural parameters, each load being applied twice for results' confirmation. The FWD load positioning was to 150 mm of joints, which used to guarantee the deflections' measures in this position as well as in the third geophone, 300 mm away from the load application center, so d_1 and d_3 were used to calculate LTE.

3.2 Initial estimate of structural parameters before the backcalculation

In order to obtain estimated start figures (seeds) for the parameters to be back analyzed, a proposed criterion by Hall [25] were used in which one determines the slab relative stiffness radius based on the deflection basin area *(AREA)* according to the *American Association of State Highway and Transportation Officials* (AASHTO [26]). This parameter is defined as follows:

$$AREA = 6 \times \left[1 + 2 \times \left(\frac{d_{30}}{d_0} \right) + 2 \times \left(\frac{d_{65}}{d_0} \right) + \left(\frac{d_{90}}{d_0} \right) \right] \quad (3)$$

d_0, d_{30}, d_{65} e d_{90} deflections are given in inches. With the AREA value, the relative stiffness radius (l_k) from the equation:

Figure 2 – FWD tests over transversal joints

Table 2 – FWD measurements program

Season	Day	Period	Central load	Loads over joints	Targets and uses
Winter 2006	07/28/2006	morning	✓	✓	Concrete modulus of elasticity Subgrade modulus of reaction (central and edge) LTE
		afternoon	-	✓	Subgrade modulus of reaction (central and edge) LTE
Summer 2007	03/26/2007	afternoon	-	✓	Subgrade modulus of reaction (central and edge) LTE
		night	-	✓	Subgrade modulus of reaction (central and edge) LTE

$$\ell_k = \left[\frac{\ln\left(\dfrac{36 - AREA}{1812{,}279133}\right)}{-2{,}559340} \right]^{4{,}387009} \qquad (4)$$

For a semi-infinite slab with loading in its central region, it is possible the analytical determination of the subgrade reaction modulus (k) once known the relative stiffness radius of the system, as proposed by Westergaard [20]:

$$k = \frac{P}{8 \times d_0 \times \ell_k^2} \times \left\{ 1 + \left(\frac{1}{2\pi}\right) \times \left[\ln\left(\frac{a}{2\ell_k}\right) + \gamma - 1{,}25 \right] \times \left(\frac{a}{\ell_k}\right)^2 \right\} \qquad (5)$$

being k given in pounds per cubic inch, *P* the applied load (in pounds-force), d_o the maximum deflection at the slab center (in inches), ℓ_k the relative stiffness radius given by equation [4] (in inches) and *a* the radius of the applied circular load by the FWD (in inches). Known the relative stiffness radius values and subgrade reaction modulus, the elasticity modulus of the concrete slab (E) is calculated by the equation for determining ℓ_k, as Westergaard [20]:

$$E = \frac{12 \times k \times \ell_k^4 \left(1 - \mu^2\right)}{h^3} \qquad (6)$$

where m is the Poisson coefficient of concrete and h is the thickness of concrete slab.

3.3 Backcalculation procedures of deflection basins by Finite Element Method

The backcalculation using the deflection envelop data from experimental slabs test track were carried out using the finite element method (FEM) program ISLAB2000 that allows numerical simulations of performed load tests in the field, providing the evaluation of the modulus of elasticity of the concrete slabs as well as the subgrade reaction modulus and LTE parameter for the real field conditions [27; 28]. In order to execute this backcalculation, 27.786 structural parameter simulations of studied concrete pavements were required (14.826 for the center load and 12.960 for the slab joint load). It is presented a simulation case of the mentioned program for joints without BT in Figure [3]; the finite element mesh for three successive slabs of an experimental slab section is represented in this mesh.

After the estimation of parameters E and k values by the criterion previously presented [25], they have been fixed as an extreme variation range for the backcalculation attempts for such parameters, a value below the lowest estimation and another value above of the highest estimation for the parameter in question. Within these ranges for the parameter combinations, simulations were performed, increasing the values and combining them with the purpose to simulate the theoretical deflection basin and compare them with measured basin in the field. In Figure [4], a backcalculation of values for E and k is exemplified, systematizing the best theoretical deflection basin (deflection envelope) found for the field measurements obtained with FWD load over slab center A2. The closeness and acceptance criterion between the backcalculated deflection basin and that one measured in the field was based on the calculation of the square error between the individual deflections of both basins according to the expression:

$$ERROR = \sum_{1}^{7} (\delta_{measured} - \delta_{ISLAB})^2 \quad (7)$$

The smallest square error of the simulation series indicates the theoretical basin that is closer to the real measured on the road. This process was carried out by successive approximations with the narrowing of parameter value range for each set of simulations. Such procedures and criteria above mentioned were also used for measured deflection basin backcalculation in the joints' vicinity of concrete slabs. In these cases, the values previously backcalculated of concrete modulus of elasticity (to slab center) were used, leaving the determination for the end process by backcalculation of the modulus of subgrade reaction values in the transverse edges (k_b) and efficiency values of load transfer in joints (LTE).

4. Results and its analysis

The LTE values were calculated according to equation [1] where they were presented individually for each load in Table [5]. Of such individual values, it is clearly noted that the BT presence in the transverse joints results in a significant increase in the LTE amount compared to the case of joints without BT when the load transfer is done exclusively by the interlocking between faces of aggregates (compare any positions with position E3). This highlights the fact that concrete pavements with BT present better performance, which is explained by more relieved stress states arising from the BT presence in joints when the load requests the pavement in this position [7].

An important aspect to be taken into account from the results presented in Table [5] is that there is an increase for LTE values calculated in slabs without BT (slab E3) due to load increase for the summer. There is no significant difference in BT slabs for these LTE values with different loading levels, in both winter and summer. This does not mean that the deflections do not change with load increasing. Based on this observation, the analyses that follow are done from the average values of all measures for the ap-

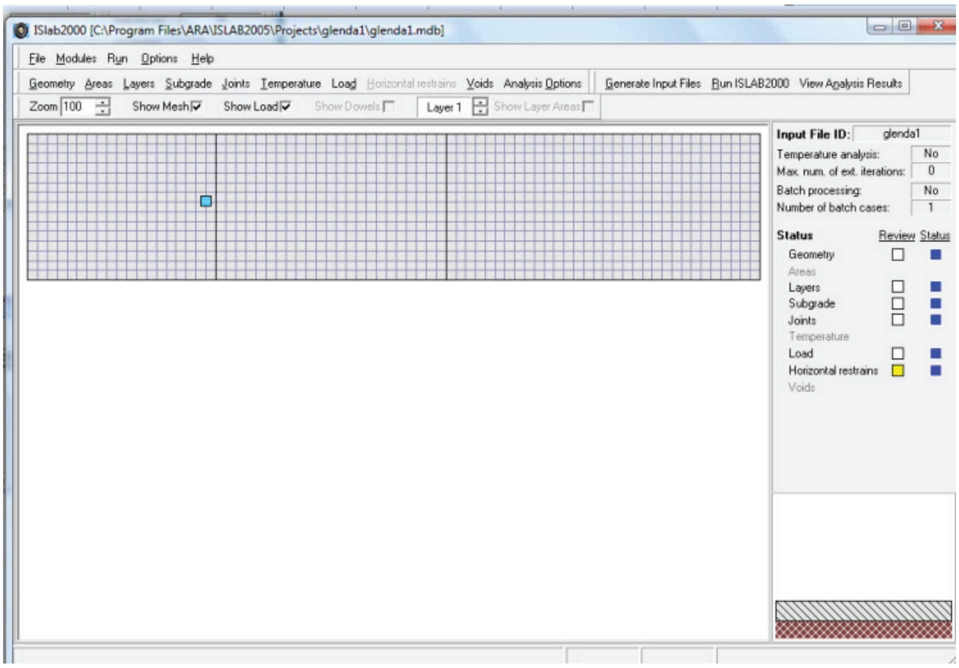
Table 3 – Thermal differentials in concrete slabs (center)

Section	FWD location	Time	Temperature (°C)	Thermal Differential (ΔT in °C)
A	A1	9:25	20.0	3.7
	A2	9:45	21.0	4.2
B	B1	9:50	19.5	3.4
	B2	9:57	19.0	3.2
	B3	10:31	23.5	5.4
C	C1	10:00	20.0	3.7
	C2	10:06	21.0	4.2
	C3	10:40	22.0	4.7
D	D1	10:08	22.5	5.0
	D2	10:12	23.0	5.2
	D3	10:50	24.0	5.7
E	E1	10:16	28.0	7.8
	E2	10:25	25.0	6.2
	E3	11:03	25.5	6.5

Table 4 – Thermal differential (°C) in concrete slabs (joints)

Section	Position	Winter – 07/28/2006						Summer – 03/26/2007					
		Morning			Afternoon			Morning			Afternoon		
		Time	T_{top}	DT	Horário	T_{top}	DT	Time	T_{top}	DT	Time	T_{top}	DT
A	A1/A2	9:32	20.0	3.8	13:35	27.0	7.4	12:30	25.0	0.3	19:35	25.5	0.5
	A2/A3	10:27	24.0	5.9	14:05	34.0	11.0	13:02	26.0	0.8	18:47	28.0	1.9
B	B1/B2	9:54	19.5	3.6	13:47	26.0	6.9	12:35	24.5	0.0	18:20	28.5	2.2
	B2/B3	10:36	24.0	5.9	14:09	34.0	11.0	13:12	31.0	3.5	18:52	26.5	1.1
C	C1/C2	10:02	20.0	4.0	13:50	32.0	10.1	12:42	41.0	12.6	18:30	32.0	7.8
	C2/C3	10:46	22.5	5.2	14:12	29.0	8.6	13:20	38.5	11.3	19:00	28.0	5.6
D	D1/D2	10:10	23.0	5.5	13:58	34.0	11.1	12:50	43.0	13.7	18:34	32.5	8.0
	D2/D3	10:55	24.0	6.0	14:14	31.0	9.6	13:30	44.5	14.5	19:04	30.5	7.0
E	E1/E2	10:20	27.0	7.5	14:00	34.0	11.1	12:56	45.0	14.8	18:42	33.0	8.3
	E2/E3	11:00	25.0	6.5	14:16	35.0	11.6	13:40	46.0	15.4	19:12	30.5	7.0

Figure 3 – Finite element mesh for simulation of FWD load test at non-doweled joint using ISLAB2000



Zoom 100

Show Mesh ☑

Show Load ☑

Layer 1

Input File ID: glenda1

Temperature analysis: No

Max. num. of ext. iterations: 0

Batch processing: No

Number of batch cases: 1

Status	Review	Status
Geometry	☐	■
Areas		
Layers	☐	■
Subgrade	☐	■
Joints	☐	■
Temperature		
Load	☐	■
Horizontal restrains	🟨	■
Voids		

plied loads as shown in Table [6]. In all slab joints, with the exception of E3 joint that does not have BT, the load transfer varies very little from morning to evening in the winter. When there isn´t a BT, LTE value increases during the afternoon, as it is clear for E3 slab (from 61.6 to 73.5%). These values are intermediate to those indicated by Vandenbossche [12] that would be of 50% in the morning and 90% in the afternoon.

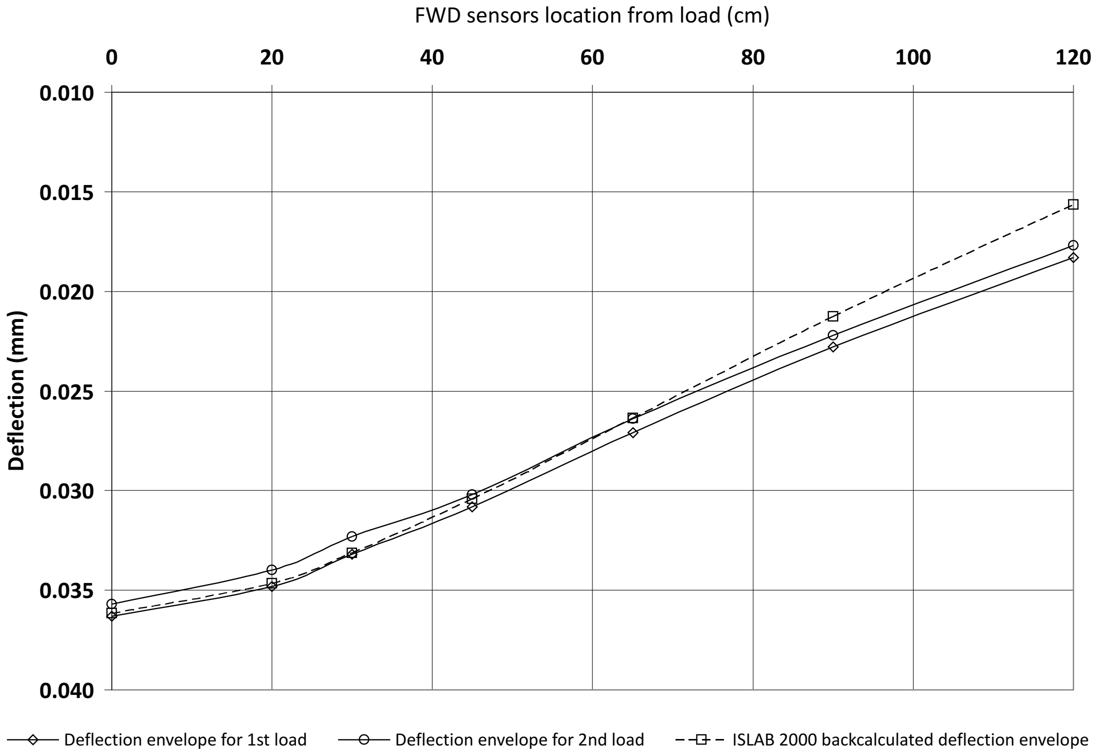
The variations between morning and afternoon and evening and night, in general, are below ± 5 percentage points, exception made to B3 slab where this variance reaches 9 to 10 percentage points. But, a variation of 10 percentage points on a basic value of 90% means a variation at about 10% in LTE. In the case of E3 slab, there is a variation of 12 percentage points on an LTE of 62%, representing an increase of at about 20% in value. This result coincides with those submitted by Shahin [1] which affirmed that in studies for slabs without BT, LTE values in the afternoon in relation to morning period ranged from 20% (positive variation). Just for the case of winter measures, it becomes apparent that in joints with dowel bars, the LTE values decrease from morning to afternoon without exceptions. Generally, this assertive is impaired, as in summer measures, this has not been verified.

These facts are well elucidated in the graphical representation of Figure [5] for the winter of 2006 and summer of 2007. During the winter, in most cases of slabs with BT, the LTE does not vary or decreases a little bit in the afternoon, and when it decreases, there aren't falls that result in inferior values less than 90% on average. 90% is taken as an excellent LTE value since the constructive system can present support deficiency in the joint vicinity, for example, reducing the LTE. However, it is noted appreciable fall in LTE value when there is no load transfer with BT, which was approximately of 95% (with BT) to 65% (without BT).

There is still an important load transfer in the case of E3 slab due to aggregate interlocking even in the absence of BT. In addition, the measures' response is fairly consistent, because with the top temperature increase at about 10ºC (see Table [4]) between the morning measure (11 am) for the afternoon measure (2 pm) in the slab E3, the LTE has increased; this means that the slab would have expanded and the joint opening, in consequence, decreased, which would cause greater interlocking between them, improving the load transfer, as it was observed in practice; in other words, there is an increase in the shear modulus of the joint interface by aggregate interlocking on this cracked surface. The conclusion is that during periods without solar radiation, when concrete resumes its original volume (construction) or contracts itself, LTE is expected to be lower even than that observed value for 11 am, in the case of BT absence in the joints. The LTE measured values in summer day, which also resulted in high values for joints with BT and reduced for joints without BT, didn´t undergo major changes over the winter.

Thus, part of the transfer, which is measured as a relation between total deflections near the joint, may be due to the base surface elastic deformation. It is not always an easy task, with measures

Figure 4 – Deflection envelope backcalculation sample (E = 55.000 N/mm^2 and k = 55 MPa/m)



of deflection values on the slab surface, individualizing what is the contribution of each layer. However, the obtained results would yet allow some speculations about the load transfer effects in differentiated situations about base type, slab thickness, as it is done in sequence. In Figure [6], LTE results are presented in relation to the applied loading level nearby slabs' joints. It is noted that in joints without BT the greater the applied load, the greater joint load transfer efficiency. In the case of slabs with BT in the joints, there aren't marked differences between the applied load levels and LTE.

In Table [7] are shown backcalculated values (with ILSAB 2000) for load transfer efficiency with tests that were performed in July, 2006 (winter) and in March, 2007 (summer). The backcalculated

Table 5 – LTE results (in %) with different FWD loads

Position	Slab	Winter 2006						Summer 2007					
		Morning			Afternoon			Afternoon			Night		
		FWD load (kN)			FWD load (kN)			FWD load (kN)			FWD load (kN)		
		47	74	84	47	74	84	47	74	84	47	74	84
A1/A2	A1	95	96	96	93	93	93	95	94	94	93	92	92
	A1	96	95	96	93	93	92	94	94	94	93	93	92
B1/B2	B1	95	93	92	90	87	87	88	87	87	87	86	85
	B1	93	94	92	87	87	87	86	86	87	86	86	86
C1/C2	C1	94	94	94	91	89	89	95	94	94	94	94	94
	C1	94	100	94	91	90	91	93	96	93	94	94	94
D1/D2	D1	94	92	90	89	88	88	91	92	91	88	89	89
	D1	94	91	91	89	88	90	89	90	91	90	89	90
E1/E2	E1	95	94	95	92	94	92	93	93	93	97	98	97
	E1	95	94	95	92	91	93	93	93	93	97	96	97
A2/A3	A3	93	94	94	91	92	92	93	97	96	96	96	96
	A3	93	92	93	92	92	92	94	95	96	96	96	97
B2/B3	B3	100	100	100	92	90	90	87	88	88	96	96	96
	B3	100	98	98	90	89	88	87	87	87	96	96	95
C2/C3	C3	91	91	91	93	92	88	84	85	87	88	90	89
	C3	92	90	90	92	89	88	84	85	87	88	89	88
D2/D3	D3	92	91	91	91	89	90	95	94	91	89	90	89
	D3	92	91	91	91	89	90	95	95	93	91	91	90
E2/E3	E3	62	63	63	77	74	72	63	67	82	62	65	68
	E3	58	62	62	70	73	73	66	75	82	57	62	67

Table 6 – Average results for LTE (%)

Slab	LTE Winter Morning/2006	LTE Winter Afternoon/2006	LTE Summer Afternoon/2007	LTE Summer Night/2007	Slab thickness (mm)	Base type	Dowel
A1	95.8	92.8	94.3	92.6	150	CS	Yes
B1	93.0	87.5	86.9	86.1	150	RCC	Yes
C1	94.9	90.0	94.2	94.0	250	RCC	Yes
D1	92.1	88.8	90.7	89.2	250	CS	Yes
E1	94.6	92.4	92.9	97.1	250	CS	Yes
A3	93.2	91.9	95.2	96.0	150	CS	Yes
B3	99.3	89.7	87.7	95.9	150	RCC	Yes
C3	90.6	90.4	85.2	88.5	250	RCC	Yes
D3	91.4	90.1	94.4	90.1	250	CS	Yes
E3	61.6	73.5	72.3	63.6	250	CS	No

Figure 5 – LTE values for winter and summer

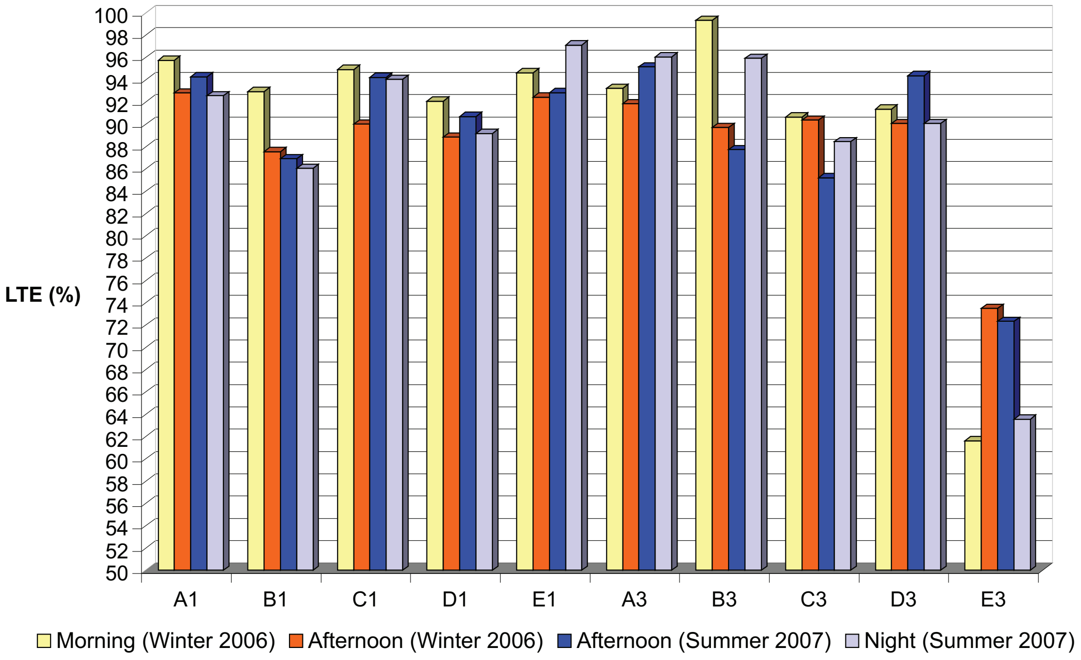
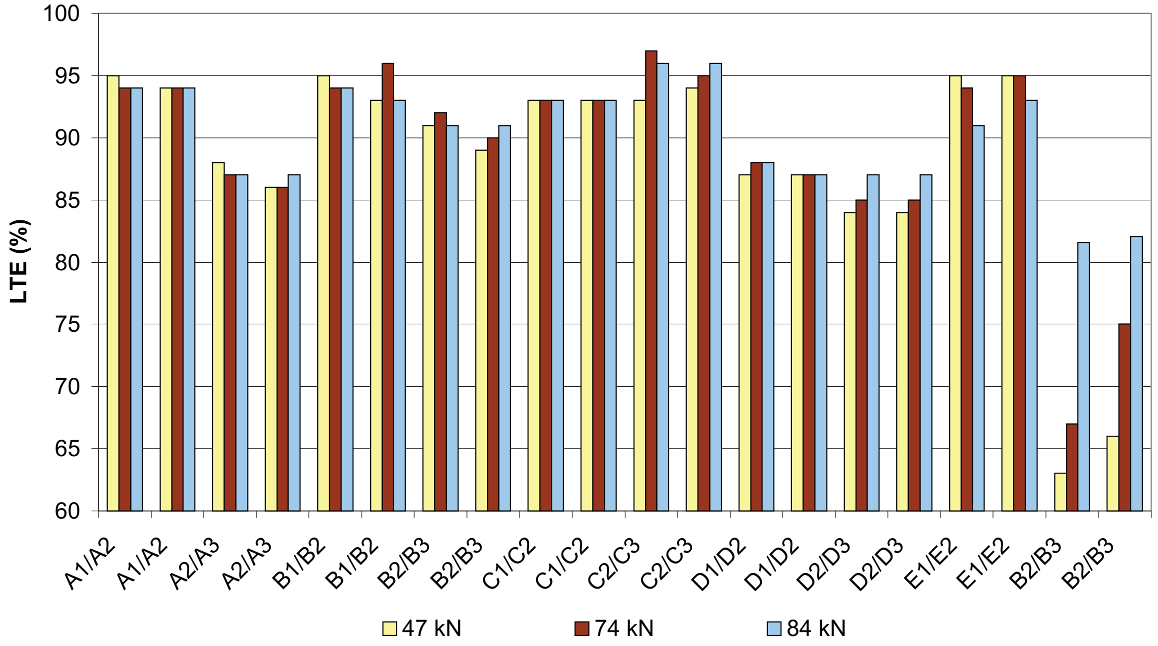


Figure 6 – Effects of load level on LTE values



LTE values in joints with BT for winter measures ranged between 90 and 99%, making it not possible to distinguish clearly effects of base type and concrete slab thickness. During the summer, these values varied between 86 and 99% again, so it is not possible to establish behavior patterns. All these values are typical of new pavements, which are justified by the non-occurrence of commercial traffic in the experimental sections, placed at a parking lot for cars. In the case of joint without dowel bar, during the winter, in the morning, the LTE was appreciably lower than that one in the afternoon (around 50% vs. 70%). In the summer, such important variations between afternoon and evening have not been verified, even because in this time of year the temperature amplitude is little than in the winter.

It is observed from the results that LTE values in dowelled joints ranged from 88 to 100%, while those obtained in non-dowelled joints ranged from 60 to 75%. In the Figure [7] such data are released one due to another, which allows us to compare qualitatively the discrepancies between measured and backcalculated LTE values. It appears that for low LTE values (<80%) cases without BT, the LTE measured values are generally higher than those that were calculated. Differently in the case of LTE in joints with BT, the backcalculated values are mostly higher than those that were calculated. Based on the average of measured and backcalculated LTE values in the field in joints with BT, as illustrated in Figure [8], it appears that the backcalculated LTE values are generally higher than the values measured in the field, in joints with BT.

Calculating the average, standard deviation and coefficient of variation of field measured and backcalculated LTE data, in the field in joints without BT, illustrated in Figure [9], the opposite is verified: measured LTE values in the field are in general larger than those backcalculated by ISLAB2000. It is also noted that the discrepancy between backcalculated and measured LTE values increases in periods in which the joint opening was greater: in the morning and at night. Thus, the ISLAB2000 program simulates critical conditions of load transfer (LTE lower values) for the same deflection measurements in the field and theoretically defined. This result corroborates with previous results using the ISLAB [29] program that indicated higher calculated stresses by the program than those with certain measures of road deformation, that is, the numerical model of ILSAB2000, in these conditions, presents the results in favor of security for project purposes. Backcalculation, however, permits its calibration for different uses.

However, the average backcalculated and measured LTE values in the field are very close, not allowing greater differentiation in the results. Including the very low results shown for standard deviation and variation coefficient, especially for joints with BT (maximum standard deviation observed was 3.4%, quite positive for measures taken in the field), which allows good reliability on obtained results through used methodology. Such results are probably tied to great construction homogeneity of the experimental slabs. The values here obtained are inferior to those that were suggested by Khazanovich and Gotlif [10]: variation coefficient around 10% for joints with BT and 40% for joints without BT; despite the fact that the survey was much broader and contemplated different aged pavements, structures and concrete conditions in general. As Colley and Humphrey [11] evidenced the load transfer in joints without BT is extremely dependent on the joint opening; this opening essentially depends on the concrete average temperature. In colder periods, with the concrete contraction, the joints are opened, causing the falling in the LTE value, which was visible in the present study. Such variations should be rigorously considered in design to forecast possible periods of critical stresses close to joints.

5. Conclusions

Based on the investigations and conducted experimental analysis, it is possible highlight and to conclude that:

- The individual LTE values shows that the dowel presence in the transverse joints results in a significant increase in its value in comparison to the case of joints without BT;
- The LTE values in non-dowelled slabs showed increase due to load intensification during and for the summer;
- There isn't any significant difference for LTE values in slabs with dowels at different levels of loading, both in the winter and in the summer;
- In all slab joints with dowels, the load transfer ranges just a little from morning to afternoon in winter;
- For the non-dowelled joint the LTE value increased during the afternoon as well as they were bigger in the summer (due to concrete expansion and increased aggregate interlock within joint lateral faces);
- The LTE values range in dowelled joints at about 10% average between afternoon and evening;
- The LTE values range in non-dowelled joints at about 20% average between afternoon and evening;
- It is noted, however, appreciable fall in LTE value when there is no load transfer with dowel, which was approximately of 95% to 65% (without dowel).

Based on well planned back analysis with ISLAB2000 program, it can also be concluded that:

- The back analyzed LTE values in doweled joints for winter measures ranged between 90 and 99%, it is not possible to distinguish clear effects of concrete slab thickness base type. During the summer, such values ranged between 86 and 99% again, not being possible to establish behavior patterns;
- In the case of non-doweled joint, in the winter, in the mornings,

Table 7 – Backcalculated values for LTE

Positon	Load (kN)	LTE (%)		LTE (%)		Positon	Load (kN)	LTE (%)		LTE (%)	
		July/2006		March/2007				July/2006		March/2007	
		Morning	Afternoon	Afternoon	Night			Morning	Afternoon	Morning	Afternoon
A1/A2	47	99	95	94	96	C2/C3	47	91	87	88	95
	74	99	95	94	99		74	91	86	88	91
	83	99	95	95	97		83	90	-	87	89
A2/A3	47	96	96	97	96	D1/D2	47	94	93	90	93
	74	92	98	96	95		74	94	92	91	95
	8	94	92	93	94		83	95	94	92	94
B1/B2	47	96	93	93	89	D2/D3	47	95	94	90	94
	74	96	94	93	94		74	93	94	90	92
	83	98	93	93	94		83	91	88	87	90
B2/B3	47	99	94	96	96	E1/E2	47	97	95	97	97
	74	99	91	98	91		74	97	92	99	97
	83	99	89	93	91		83	99	94	98	97
C1/C2	47	95	95	93	95	E2/E3	47	55	64	58	74
	74	98	95	96	94		74	53	62	60	71
	83	97	95	94	94		83	49	71	58	70

the LTE was appreciably lower than that one in the afternoon (around 50% vs. 70%);

- For low LTE values (< 80%), case without dowel, measured LTE values are generally superior to those ones that were calculated. Differently, in the case of LTE in joints with dowels, the backcalculated values are mostly superior to those that were calculated.
- The average of back analyzed and measured LTE values in the field are very close, with standard deviation and variation coefficient very small, not allowing greater differentiation in the results.

Figure 7 – Comparison of backcalculated and measured LTE values for doweled joints

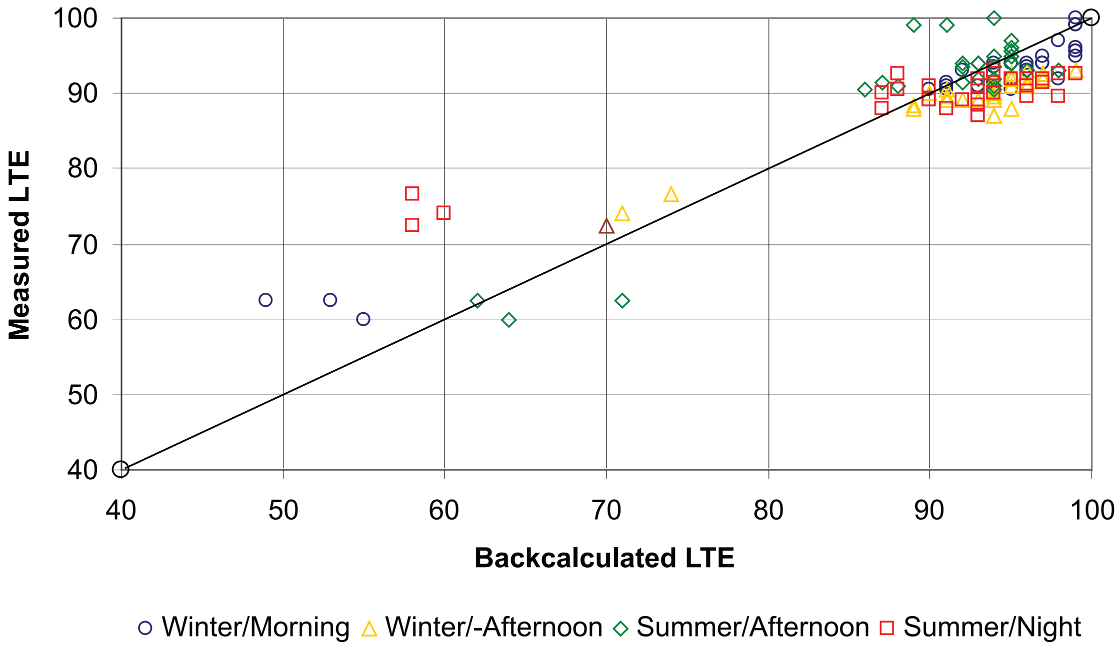
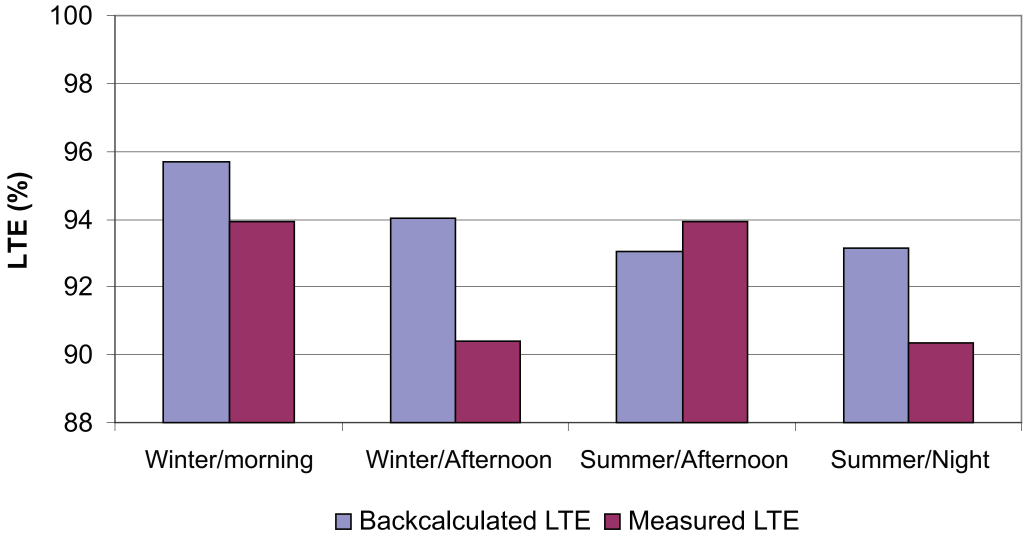


Figure 8 – Comparison of backcalculated and measured LTE values for doweled joints (by season)



The obtained results pointed out the need for explicit consideration of LTE variations in the behavior of concrete slabs without dowel bars for paving, because according to the time of day or season, effort transfers in joints changes a lot, which causes variations in the distribution of stresses in these project critical elements.

5. Acknowledgments

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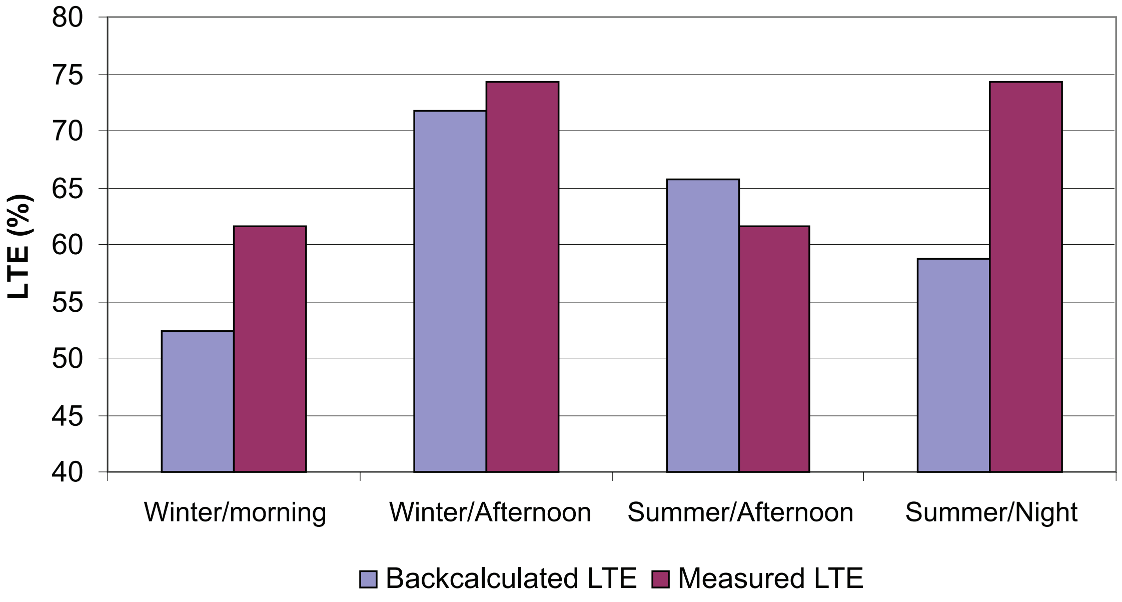
Figure 9 – Comparison of backcalculated and measured LTE values for joints without dowels



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