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Experimental evaluation of load transfer efficiency of non-dowelled concrete pavements

Authors:

Assist.Prof. Mauricio Pradena, PhD. CE
Departamento de Ingeniería Civil
Universidad de Concepción, Concepción, Chile
mpradena@udec.cl
Corresponding author

Assoc.Prof. Lambert Houben, PhD. CE
Delft University of Technology, Netherlands
Section Pavement Engineering
L.J.M.Houben@tudelft.nl

Andrés César, MCE
Departamento de Ingeniería Civil,
Universidad de Concepción, Concepción, Chile
acesar@udec.cl

Research Paper

Mauricio Pradena, Lambert Houben, Andrés César

Experimental evaluation of load transfer efficiency of non-dowelled concrete pavements

Generally, joint performance in concrete pavements is evaluated in laboratory by applying dynamic loads that require large scale experimental setups. In order to propose a simplified laboratory test, a comprehensive literary review of the fundamentals of load transfer at joints is made, and the load transfer efficiency obtained via a reduced scale test is compared under static and dynamic conditions. The results confirm feasibility of static analysis via a reduced scale test for evaluating load transfer efficiency of non-dowelled concrete pavements.

Key words:
concrete pavements, load transfer, laboratory test, aggregate interlock, crack width, dynamic loads, static test, short slabs

Prethodno priopćenje

Mauricio Pradena, Lambert Houben, Andrés César

Eksperimentalna ocjena učinkovitosti prijenosa opterećenja na betonskim kolnicima bez moždanika

Ponašanje spojeva u betonskim kolnicima u laboratorijskim se uvjetima uglavnom ocjenjuje nanošenjem dinamičkih opterećenja za koje je potreban zahtjevan postav eksperimenta. Predlaže se pojednostavljeno laboratorijsko ispitivanje, te se u tom kontekstu daje opsežan pregled literature o osnovama prijenosa opterećenja na razdjelnicama. Učinkovitost prijenosa opterećenja uspoređuje se u statičkim i u dinamičkim okolnostima primjenom pokusa u umanjenom mjerilu. Rezultati potvrđuju prikladnost primjene statičke analize u umanjenom mjerilu za ocjenu učinkovitosti prijenosa opterećenja na betonskim kolnicima bez moždanika.

Ključne riječi:
betonski kolnici, prijenos opterećenja, laboratorijsko ispitivanje, uklještenje agregata, širina pukotine, dinamička opterećenja, statičko ispitivanje, kratke ploče

1. Introduction

Jointed Plain Concrete Pavements (JPCPs) are a conventional type of concrete pavements. These pavements consist of unreinforced concrete slabs with transverse contraction joints between the slabs. The distribution of these joints is calculated in such a way that the spacing between them prevents formation of cracks in slabs until late in the life of the pavement [1]. When a slab-on-grade is subjected to wheel load, it develops bending stresses and distributes the load over the foundation. However, the response of these finite slabs is controlled by edge or joint discontinuities [2]. Actually, the load transfer across contraction joints is an important issue in JPCPs performance [1]. This transfer is provided by two methods, the dowel bars and aggregate interlock (Figure 1) [3]. In the first case, the load transfer mechanism relies almost exclusively on each bar's shear resistance. On the other hand, in the aggregate interlock, load mechanism is transferred via shear forces produced by mechanical interaction of aggregate particles at the cracks under the pavement joints (Figure 1c). Hence, in non-dowelled pavements, the aggregate interlock is the main load transfer mechanism at transverse joints [4], where the Crack Width (CW) under the joints is the direct cause of the ability to transfer the load applied on one slab to the other, i.e. of the Load Transfer Efficiency (LTE) [5-8].

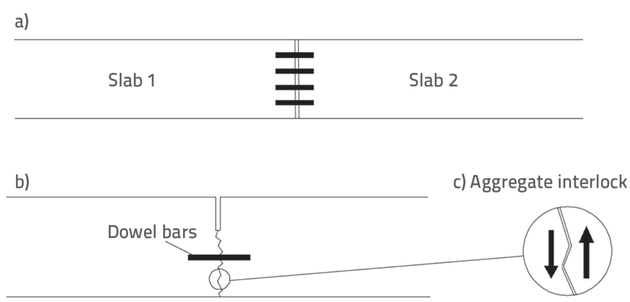

Figure 1. Representation of load transfer mechanisms in jointed plain concrete pavements: a) Top view of JPCP section; b) Transverse slabs section view; c) Aggregate interlock mechanism

Currently, LTE is used as an input parameter in mechanistic methods of structural concrete pavement design [9-13]. However, in these methods, the LTE is a fixed value (or values) defined by indirect causes, i.e. without considering the CW.

In addition, the experimental study of LTE is traditionally performed in the field or in large scale laboratory tests (Figure 2) [14-18]. These kinds of LTE experimental evaluations require appropriate resources, which are not easily available.

The aim of the present paper is to propose a practical laboratory test aimed at evaluating the LTE of non-dowelled jointed plain concrete pavements, particularly of short concrete slabs. The purpose behind the proposal is that the LTE can be experimentally evaluated in concrete laboratories with traditional equipment. This can contribute to better definition of the LTE values for structural pavement design methods. The proposal is based on a review of the LTE mechanism, the existing methods to evaluate it, and the comparison of field and laboratory results of LTE with the proposed test.

Figure 2. Large scale test set up for evaluating load transfer efficiency [19]

2. Load transfer in concrete pavements

2.1. Load transfer efficiency

In JPCPs, when a load is applied near a joint, the loaded slab and the adjacent unloaded slab experience some level of deflection. These deflections depend on the joint capability to transfer a part of the load between both slabs. [20]. Hence, the in-service pavement performance depends on the LTE at joints. Actually, early deteriorations can developed as a result of poor LTE [21].

LTE is quantified through dimensionless combinations of deflection or bending stress [22]. The deflection load transfer efficiency (LTEδ), often abbreviated simply as LTE (Eq.1), and stress load transfer efficiency (LTEs) (Eq. 2), are defined as follows:

$$LTE\delta = \frac{\Delta_U}{\Delta_L} \tag{1}$$

$$LTEs = \frac{\sigma_U}{\sigma_L} \tag{2}$$

Where Δ_u and σ_u are the deflection and stress of the unloaded slab, and Δ_L and σ_L are the deflection and stress in the loaded slab respectively.

Nevertheless, computation of deflection LTE is commonly used to measure load transfer in concrete pavements [23] and it is the one applied in the present contribution. LTE of 100 % represents the ideal condition where both sides of the joint share the load equally, and 0 % indicates the worst condition where no load is transferred from the loaded to the unloaded side (Figure 3) [24]. Generally, LTE amounting to 70 % is accepted as the value that assures an adequate performance of the in-service JPCP [20, 25, 26].

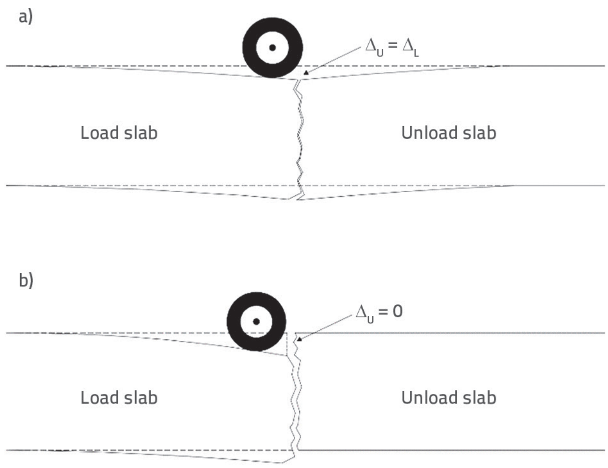

Figure 3. Representation of joint performance: a) Good load transfer (LTE = 100 %); b) Poor load transfer (LTE = 0)

2.2. Load transfer mechanism on non-dowelled JPCPs

When dowel bars are not used, aggregate interlock is the main load transmitting mechanism [4,17]. Generally, the pavements that depend exclusively on aggregate interlock are found on roadways with low volume of traffic, [1, 22, 27, 28]. However, there is evidence of regions where this mechanism without dowel bars can be effective under more demanding conditions, even becoming a common practice, as it is the case of JPCPs in Chile, for instance [16, 29].

Furthermore, new paving technologies are emerging where aggregate interlock load transfer plays a major role. Such is the case of short concrete slabs as a paving solution [18, 29-33]. The short slabs pavement is a patented design methodology [30, 31] that proposes to reduce the dimensions of slabs, depending on traffic volume, in such a way that no more than one set of wheels remains on the slabs (Figure 4). In addition to the new traffic load configurations, there is less slab length available to curl. Hence, tensile stresses and curling stresses are reduced. Furthermore, the standard design method does not incorporate load transfer mechanism by dowel bars [31, 34]. Therefore, the transfer of load is mainly operated by aggregate interlock.

Indeed, Roesler *et al* [18] confirmed that short slabs are capable of maintaining an adequate level of LTE. However, that investigation did not establish a direct relationship between the LTE and the mechanism that acts in this system i.e. the aggregate interlock. Related to this, while calibrating a mechanistic empirical pavement design method for short slabs, Salsilli *et al* [29] identify the necessity to develop specific studies of LTE for this pavement innovation.

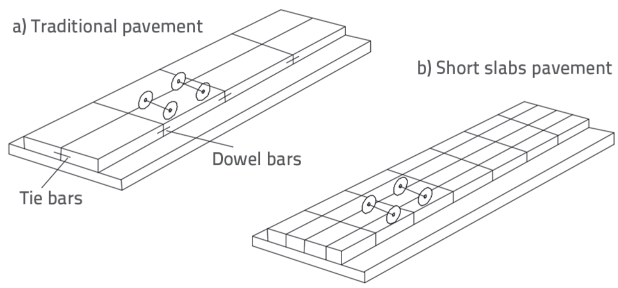

Figure 4. Traffic load axle distribution: a) Traditional pavement; b) Short slab pavement

In non-dowelled concrete pavements (traditional or short slabs), the provision of LTE by aggregate interlocking is based on the irregularities of crack faces. In effect, when a crack develops in a joint of a concrete pavement, the aggregate and the irregular texture of the cement matrix make the crack faces rough and irregular [35].

When a wheel load approaches a crack, differential vertical displacement of the two slab takes places, causing the particles of one face of the crack to come into contact with the one of the other face [35, 36]. In this way, the load transfer by aggregate interlock is a pure shear mechanism [21] that provides continuity to the pavement and avoids isolation of the slabs (Figure 1c).

Despite the importance of aggregate interlock in pavement performance, limited experimental investigations concerning this subject are currently available. One of the first research activities was carried out by Colley and Humphrey [14]. They developed a test device for applying repeated loads in such a way to simulate the action of a vehicle passing over the joint. From this test, variations of LTE were observed in relation to joint spacing, slab thickness, foundation type, type and shape of the aggregate, load magnitude, and number of load repetitions. The test methodology and the reported results have been the basis for future research [37-39].

In 2001, Jensen and Hansen [15] studied the LTE-CW relation in two types of representative American aggregates (glacial gravel and limestone). At the end of the work they concluded that it is possible to differentiate three performance states. The first corresponds to CW up to 0.5 mm where the LTE is close to 100 %. The second state is identified for CW ranges between 0.6 mm and 2.5 mm, where aggregate interlock predominates as the load transfer mechanism. Finally, when the 2.5 mm CW is exceeded, the aggregate interaction practically disappears, and so the load transfer must be supported by another system.

Gradual reduction of LTE with an increase in CW is the traditional behaviour reported by other authors [20, 21, 39, 40]. However, in South Africa, Hanekom *et al* [4] compared the LTE obtained from laboratory slab tests with the results reported by Jensen and Hansen [15] and the finite element model EverFE, which was validated with the data of Colley and Humphrey [41]. The results revealed that the load transfer reached in the South African case was significantly higher than the ones involving American aggregates and the EverFE program. Moreover, the South African values present a singular behaviour where, with an initial increase in CW, the LTE is reduced to a point where this reduction is limited, presenting an almost asymptotic behaviour as the CW increases.

A similar behaviour was reported by Pradena and Houben [42] during evaluation of short-slab test sections in Chile. As an explanation of this behaviour, the authors suggest that the high quality of the aggregates used for the test contributed to an improved performance of the LTE-CW relation. The hardness of the aggregate ensures that the cementing matrix is the weakest component of the system. Therefore, the crack occurs through the matrix but along the circumference of aggregate particles [6]. In fact, Hanekom *et al* [4] used aggregates markedly superior to those used by Jensen and Hansen [15] which, although being the softest South African aggregate (elastic modulus of 29 GPa), are superior to the hardest American aggregate (elastic modulus of 24 GPa).

2.3. Dynamic and static LTE comparison background

Wadkar *et al* [20] calculated the LTEs under dynamic load. The results were compared with the LTEs under static load, derived from the 2D finite-element (FE) program JSLAB 2002, and deflection field measurements with the Falling Weight Deflectometer (FWD). The values of the LTEs under static load were on an average by 38 % lower compared to those related to dynamic loads. In fact, Darestani *et al* [23] also established that the LTE value of transverse joints under dynamic load is slightly higher than that obtained under static load.

Hanekom *et al* [4] and Brink *et al* [38] have investigated in laboratory the difference in pavement response to static and dynamic loads in terms of deflections across the joint. After 2 million dynamic load cycles there were no significant deteriorations in the faces of the cracks, which indicates that slight aggregate abrasion at the joint face is not significant. Actually, Hansen (2003) confirmed this fact through follow-up testing conducted on the experimental slabs used in the study of Jensen and Hansen (2001) [44]. It should be noted that this characteristic was reported despite the fact that Jensen and Hansen [15] use aggregates notoriously inferior to those selected by Hanekom *et al* [4].

Moreover, Brink *et al* [38] performed static load tests for every 0.5 million load applications and the data were analysed to determine general trends. In all cases, the LTE was greater under dynamic load.

Focused on providing a method to define a practical LTE-CW relation for traditional concrete laboratories, Pradena *et al* [45] developed a test for the evaluation of joint performance on a reduced scale. In the first phase, they analysed the LTE behaviour of short-slab sections in Chile and compared the results with those of the static load test (using the same aggregates that were used on test sections). The LTE of the test proved to correlate adequately with what was observed in the field. However, due to the controlled laboratory conditions, the tests delivered higher values of LTE. Although Pradena *et al* [45] concluded that it is possible to develop the LTE-CW relation from this method, it is still necessary to evaluate the response under dynamic load.

3. Proposed laboratory evaluation of LTE

3.1. Test set up

Some efforts to develop test methods that simplify the evaluation of joint performance can be found in literature [46, 47]. These proposals are based on the use of a beam of dimensions that are similar to the ones used for concrete flexural tests. This type of beams is tested under cyclic loading. The equipment necessary for the execution of the test can still be a limitation for traditional concrete laboratories of many regions, mostly because of the use of cyclic loading. In order to facilitate the experimental LTE evaluation and overcome this limitation, the present proposal was developed during a research stay at the Delft University of Technology (TU Delft) in the Netherlands, where it was possible to compare LTE results under static and dynamic load for the proposed laboratory setup. Based on the proposal of Thompson [46] and Arnold *et al* [47], the sample preparation consists on inducing two cracks in a beam, in such a way that three sample sections are generated. The sample was placed in a loading frame and the space between sections was adjusted to the CW of interest. Afterwards, the lateral sections were strapped off the wooden blocks on the upper faces, and metal plates on the side faces with the 100 mm central block were free to move once the load was applied (Figure 5).

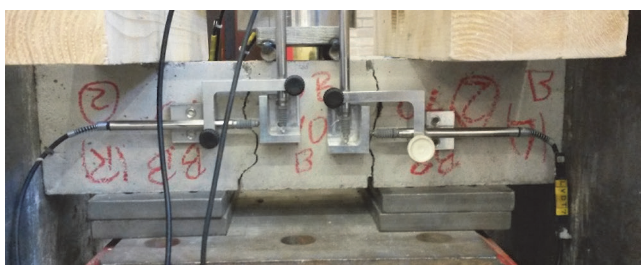

Figure 5. Experimental setup

This setup causes a load differential between both sides of the cracks, which produces a double shearing stress and reduces the risk of rotation [46, 47]. For this reduced scale test, Pradena *et al* [45] determined that the application of the 4 KN load in the central section produces the stress of 250 KPa, which is equivalent to the shear stress at the in-service JPCP when a load of 80 kN standard axle (40 kN per wheel) is applied.

Additionally, Pradena *et al* [45] propose Eq (3) to determine the LTE through vertical Relative Movement (RM) registered by the Linear Variable Displacement Transducers (LVDTs) placed vertically on both sides of the beam.

$$LTE = \frac{100 - 100RM}{1 + RM} \tag{3}$$

The aggregate interlock mechanism is produced by the interaction of the crack faces, which are irregular by nature. Hence, due to the intrinsic irregularity of the mechanism, slight variations may occur between sample results. Therefore, despite the fact that the experiments are carried out in laboratory-controlled conditions, some variability associated with the mechanism can be noted [45].

The test configuration takes advantage of having two cracks per beam; the data on the behaviour of both cracks are registered using vertical LVDTs. Furthermore, two LVDTs per side are placed horizontally to monitor the CW.

The purpose of simplification of the test is to enable the study of the aggregate interlock mechanism in a practical way using aggregates of sizes typically applied in JPCPs, i.e. mostly 20 mm and 40 mm maximum aggregate size [13, 48], and within the range of CW expected at in-service JPCPs. For the specific case of short slabs JPCPs, the CW is less than 1.5 mm [49] and therefore the aggregate interlock predominates as a means of load transfer. In effect, previous investigations have concluded that the base starts to play a role in the provision of LTE only as from CW of 2.5 mm [4,15, 45].

Further information about the development and set up of the test can be found in Pradena *et al* [45].

3.2. Aggregate characterization

Two Chilean aggregates were characterized in TU Delft. In order to define the quality of the aggregates, the characterization included the following tests: Micro Deval (MD), Aggregate Impact Value (AIV), and Aggregate Crushed Value (ACV). The results, summarized in Table 1, were compared with standard requirements for the use of aggregates in JPCPs, according to OPSS 1002 [50] for MD and as per BS 882 [51] for AIV and ACV.

The aggregates comfortably satisfy requirements provided in the specifications. In fact, the value of AIV is within the range of 10 % and 20 %, which is considered the zone of strong aggregates [52].

Table 1. Characterization of aggregates

Tests \ Aggregate	Aggregate 1 [%]	Aggregate 2 [%]	Specification limit [%]
Aggregate impact value (AIV)	11	10	30
Aggregate crushed value (ACV)	12	11	30
Micro deval (MD)	11	7	14

The hardness of the aggregate stands out once again when comparing the results of ACV with typical values of rocks such as basalt and andesite (ACV of 13 % and 14 % respectively), which are considered strong rocks [53].

Additionally, the aggregate has more than 50 % crushed particles satisfying the minimum requirement for concrete pavements [48].

4. LTE results analysis and discussions

4.1. Dynamic and static comparison

Initially, the dynamic case evaluation involved load application in up to 1 million repetitions. However, as changes in samples were negligible, the decision was made to increase the repetitions for the condition where the aggregates had greater interaction and stability. Therefore, the load was applied cyclically in up to 5 million repetitions for CW 0.5 mm and 1 million repetitions for CW 1.5 mm.

The results under static and dynamic loads of aggregate 1 exhibit slight differences. For the 40 mm beams at CW 0.5 mm the dynamic test presents LTE values between 95 % and 99 %, resulting in an average LTE of 97 %. Meanwhile, the static case (zero repetitions) maintains a slightly lower LTE average of 96 % (Figure 6a).

Similarly, for a CW 1.5 mm, the average LTE for the dynamic case is 95 %, while it is 94 % for the static case (Figure 6c).

At CW 0.5 mm, the LTE between 97 % and 99 % was registered for aggregate 2 with 40 mm in maximum grain size. The results reveal small variation in the LTE with an increase in the number of cycles. It should be noted that in some cases the most demanding conditions (greater repetitions) are those that present higher LTE values (Figure 6b).

A slight reduction of LTE values occurs when the CW increases to 1.5 mm. The dynamic LTE recorded for 40 mm ranges between 94 % and 95 %. The static result is again lower, with an average LTE of 93 % (Figure 6d). This behaviour is similar to that of aggregates with 20 mm in maximum grain size (Figure 7).

Figures 6 and 7 show that there are no large differences between dynamic results. As Brink *et al* [38] concluded, the results suggest that under dynamic load, small abrasions

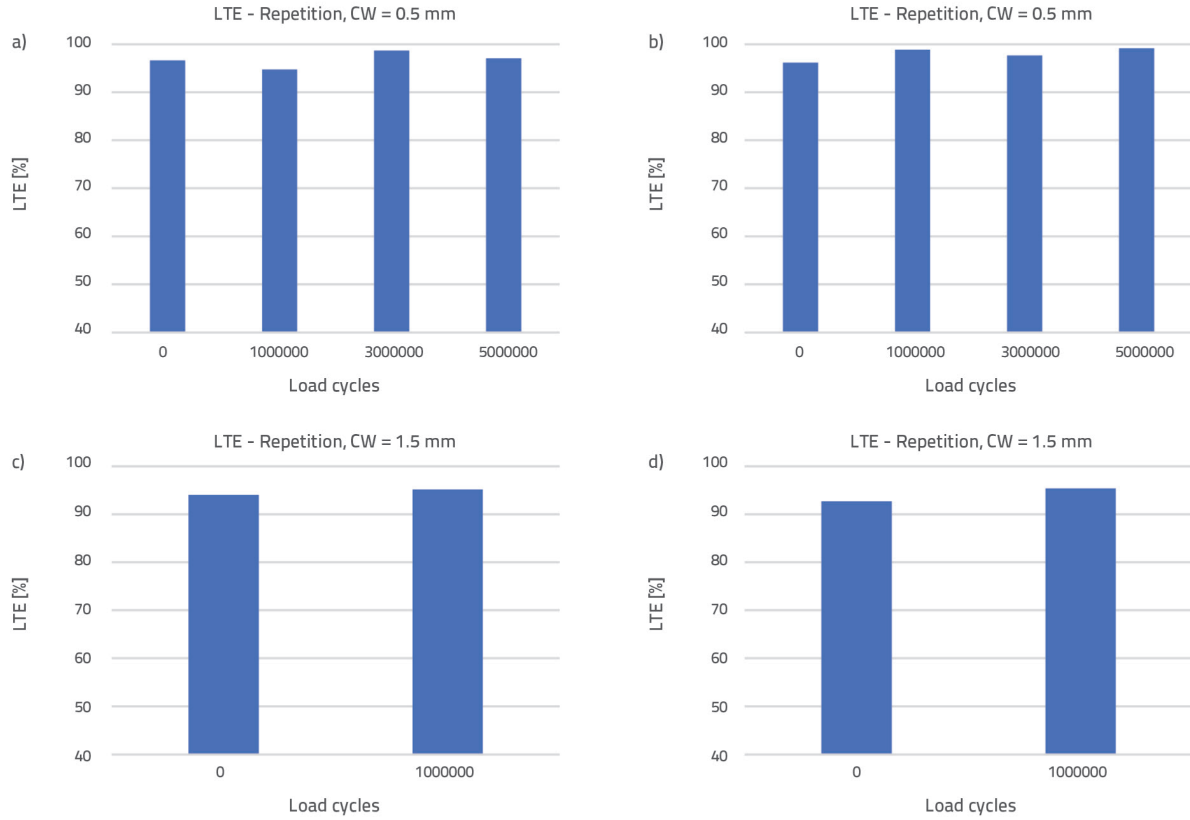

Figure 6. LTE in relation to the number of cycles, 40 mm maximum size: a) Aggregate 1, CW = 0.5 mm; b) Aggregate 2, CW = 0.5 mm; c) Aggregate 1, CW = 1.5 mm; d) Aggregate 2, CW = 1.5 mm

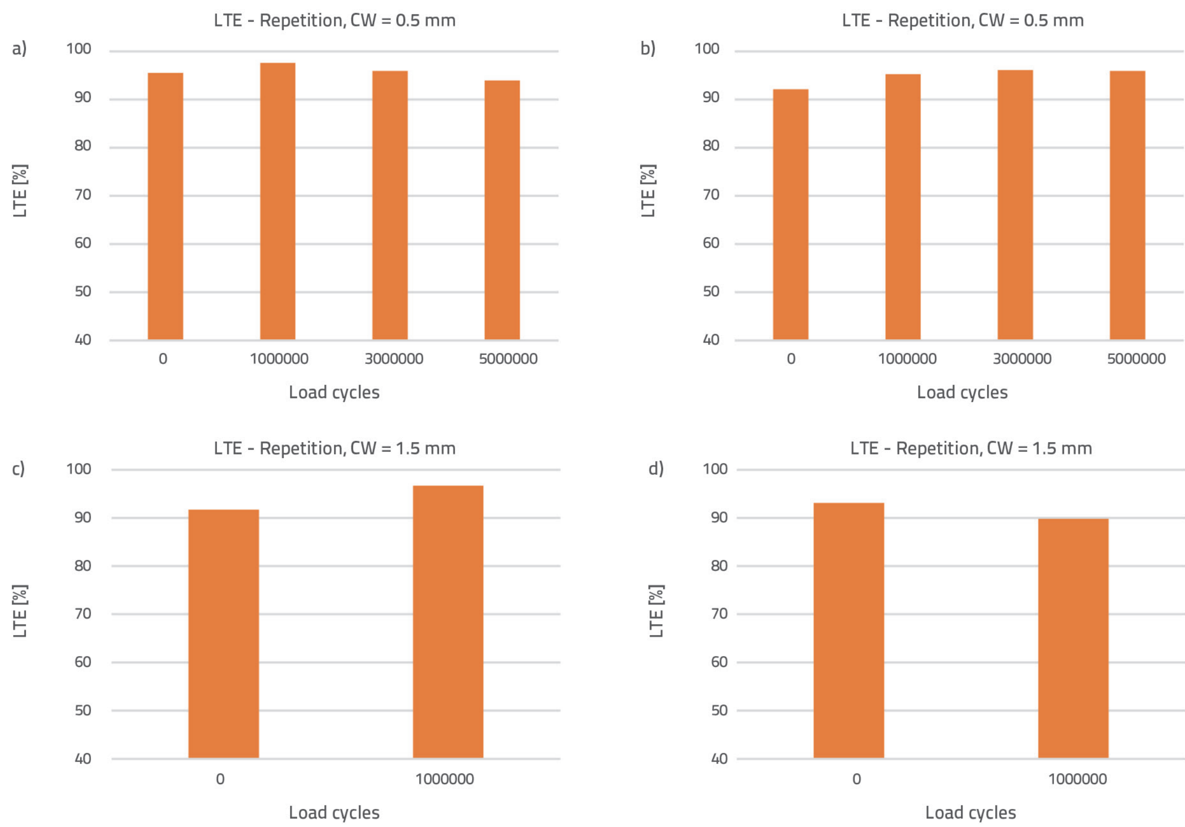

Figure 7. LTE in relation to the number of cycles, 20 mm maximum size: a) Aggregate 1, CW = 0.5 mm; b) Aggregate 2, CW = 0.5 mm; c) Aggregate 1, CW = 1.5 mm; d) Aggregate 2, CW = 1.5 mm

on the faces of the cracks do not play a significant role. Therefore, the results remain constant throughout the test. In fact, the standard deviation of dynamic results is less than 2.0 %.

The greater provision of LTE under dynamic load agrees with the results of Hanekom *et al* [4] and Darestani [43] who reveal that the LTE at joints is slightly greater under dynamic loads compared to static load.

Finally, it is very important to highlight that both the dynamic and static cases present LTE values of over 89 %, the LTE 70 %, being the accepted value that ensures an adequate performance of the in-service JPCP [20, 25, 26].

4.2. Discussion

The proposed test allows definition of the LTE value as related to CW, which is the direct cause of the ability to transfer loads between slabs in non-dowelled JPCPs [5-8]. The calculation of CW for JPCPs under various conditions can be done using formulas, such as the ones of the American Association of State Highway and Transportation Officials (AASHTO), the Mechanistic-Empirical Pavement Design Guide (MEPDG), or by means of a system approach as the one proposed by Pradena and Houben [55].

Considering that pavement structural design methods currently suggest fixed LTE values which are, in general, obtained from indirect variables [9-13], this proposal represents an advance in practical definition of the LTE for its subsequent incorporation into pavement design methods. Although it is advisable to study this mechanism at a greater number of repetitions, the LTE by aggregate interlock showed a favourable performance under the cycles evaluated in laboratory, being slightly lower under zero cycles (static case).

These data show that slightly more conservative design values are obtained during evaluation of LTE performance under static load for pavements with low to medium traffic volumes.

A direct application is found in the evaluation of short slab JPCPs. These pavements have been shown to have enough LTE without load transfer devices for low to medium traffic [18]. In fact, although Cervantes and Roesler [54] did not establish LTE-CW relations, they recorded test sections where the LTE remained above 70 % after 57.5 million Equivalent Single Axle Loads.

Additionally, the good LTE response for the static and dynamic case is explained by the use of hard aggregate. Hard aggregates ensure that, during the development of the crack, the cement matrix bordering the aggregate is crossed, which favours the aggregate interlock [6].

For this reason, the definition of the LTE-CW relation through the static load test has special relevance for the case where hard aggregates are used. Additionally, a static test at a reduced scale can allow traditional concrete laboratories to evaluate the JPCPs joint performance, relating the load transfer to the cause that explains the mechanism, i.e. the CW.

Furthermore, although soft aggregates require more investigation, it is advisable to apply hard aggregates in non-dowelled JPCPs, where an adequate LTE of the in-service pavement can be maintained even without dowel bars.

5. Conclusion

The present article proposes a practical laboratory test for the evaluation of LTE in non-dowelled JPCPs. The proposal of a test at reduced scale is based on the literature about fundamentals of load transfer by aggregate interlock, and on the analysis of relevant methods.

The results obtained with the proposed test when applying dynamic load do not show noticeable changes in the LTE response. This fact confirms that, for medium load applications, deterioration by abrasion on the faces of the joints is not significant. This behaviour is explained by the hardness of the aggregate, which ensures that cracking occurs only in the cementitious matrix favouring the aggregate interlock.

On the other hand, the LTE value under static load was slightly lower than the LTE value for dynamic load. However, the behaviour of LTE in relation to the CW was similar. This fact confirms that at least in cases where hard aggregates are used, the LTE obtained from static load is slightly more conservative than the dynamic LTE. This is especially attractive when considering ways to simplify the tests currently used for the evaluation of LTE.

The static test proposed is a practical way to evaluate LTE in traditional concrete laboratories and avoid the need for large work equipment, space, and resources. Additionally, it allows establishment of the LTE-CW relation. The proposed test can therefore contribute to the definition of the LTE by the cause that explains its performance, rather than by indirect factors. For the purposes of structural design of pavements, this relation represents a better definition of the LTE.

The provision of LTE presented during the tests shows that it is possible to obtain a good performance of joints without requiring dowel bars. Therefore, it is advisable to apply hard aggregates that ensure good behaviour of LTE in-service pavements, thus saving time and construction cost. This is especially valid for crack widths of less than 1.5 mm, which is the case of short slab JPCPs.

Acknowledgements

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