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Influence of early-age behaviour on structural design of sustainable thinner concrete slabs

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Research Paper

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Influence of early-age behaviour on structural design of sustainable thinner concrete slabs

The load transfer efficiency (LTE) of non-dowelled jointed plain concrete pavements (JPCPs), such as the innovative short slabs, is defined in terms of the cracks that form under the joints at an early age. The authors had previously developed and calibrated a model to predict crack widths in traditional JPCPs. The aim of this study is to validate this model using short slabs to relate crack width and LTE. After comparing the predicted crack width with actual ones observed in urban, industrial, and interurban short slab JPCPs, it is concluded that the model is useful for incorporating the early-age concrete behaviour into the structural design of these sustainable thinner slabs.

Key words:
early-age, concrete pavements, short slabs, structural design, load transfer, thinner slabs

Prethodno priopćenje

Mauricio Pradena, Lambert Houben

Utjecaj ponašanja svježeg betona na projektiranje održivih tanjih betonskih ploča

Učinkovitost prijenosa opterećenja (load transfer efficiency - LTE) na dilatiranim betonskim kolnicima bez moždanika (jointed plain concrete pavements - JPCP), kao što su inovativne kratke ploče, određena je prema pukotinama koje se stvaraju ispod razdjelnica dok je beton svjež. Autori su prethodno razvili i kalibrirali model za predviđanje širine pukotina u tradicionalnim JPCP-ovima. Cilj prikazanog istraživanja je potvrditi ovaj model korištenjem kratkih ploča kako bi se utvrdila veza između širine pukotina i LTE-a. Nakon usporedbe predviđene širine pukotina s onima uočenim u urbanim, industrijskim i međugradskim JPCP-ovima s kratkim pločama, zaključuje se da je model koristan za uključivanje ponašanja svježeg betona pri projektiranju održivih tanjih ploča.

Ključne riječi:
svježi beton, betonski kolnici, kratke ploče, projektiranje kolnika, prijenos opterećenja, tanje ploče

1. Introduction

Short concrete slabs are an innovation of traditional jointed plain concrete pavements (JPCPs). The reduction in joint spacings provides a new traffic load configuration for the slabs as well as a reduction in slab curvature, which allows the slabs to withstand more traffic loads than traditional JPCPs having the same thickness [1] or reduces the thickness of JPCPs needed to support the same traffic demands [2]. This not only results in a more sustainable alternative (less concrete) but also allows for lower initial construction costs. The savings can be up to 25% since the joints of short slabs are also undowelled and unsealed [2, 3]. Other design features of short slabs are as follows: slab length < 2.5 m; granular base with limited fines content (≤ 6% to 8% passing 75 μm); thin saw-cut at joints (2–3 mm thick); no dowel or tie bars [4].

Some aspects of the short slab technology have been patented by a private Chilean company [5-7]. This situation combined with the continued interest in applied research and pavement innovations by the National Highway Laboratory of Chile have resulted in a concentration of test sections and projects related to short slabs in Chile. The research on the development of short slabs has mainly focused on the structural analysis of this innovation [1-4, 8-12].

Although short slabs are non-dowelled JPCPs, there have been no specific studies on the relationship between the LTE caused by aggregate interlock and its direct cause (the crack width) with regard to this state-of-the-art innovation. Considering that the provision of load transfer relies on aggregate interlock, which is the most influential load transfer mechanism in non-dowelled JPCPs [13-15], the characterization of the relationship between LTE and crack widths is fundamental. For this, it is necessary to not only know the LTE at short slabs but also relate it with the aggregate interlock defined by the crack width at transverse joints, which is the direct cause of the LTE in non-dowelled JPCPs used as short slabs.

Pradena and Houben [16] developed the relationship between the load transfer and crack width (at joints) specifically for innovative non-dowelled short concrete slabs pavements. Houben [17, 18], Pradena [19] and Pradena and Houben [20, 21] developed and calibrated a model to predict crack widths at the joints of traditional JPCPs. The aim of this study is to validate that model using short slabs to obtain the relationship between crack width and LTE in order to incorporate the early-age concrete behaviour in the structural design of short slab JPCPs.

Model validation is the process of confirming that the predictions of a model represent measured physical phenomena [22]. The main idea behind validation is to examine whether a model can be used for prediction purposes. Validation compares simulated system output to real system observations using data not used in the model development [23].

2. Modelling the cracking process of JPCPs

The prediction of the cracking process in JPCPs is a very challenging process involving numerous variables. Even a detailed system like the Mechanistic–Empirical Pavement Design Guide (MEPDG) uses a simplified formula for the estimation of crack width under the joints [24]. In this study, the cracking process of JPCPs is predicted using a detailed rational model, which considers the JPCP as a system in which the modelling of the cracking process is not only time-dependent but also space-dependent, i.e., it includes the interaction of a group of joints [18, 21]. In this approach, the changes in the concrete since early-age are modelled by the development of the concrete properties with respect to time, the drying and autogenous shrinkage (according to Eurocode 2: Design of Concrete Structures – Part 1-1: General rules and rules for buildings [25]), and the thermal deformation rather than fixed mean values as in the AASHTO simplified formula [26]. In this section, only a brief description of the model is provided. The details of the model can be found in Houben [17, 18], Pradena [19] and Pradena and Houben [20, 21]. The basic formulation is that the tensile stresses that occur in a JPCP are caused by restricted deformation, as predicted by Hooke's law, but are influenced by the viscoelastic behaviour of the concrete (relaxation)

$$\sigma(t) = g \cdot R \cdot E(t) \cdot \varepsilon(t) \tag{1}$$

where E(t) is the time-dependent modulus of elasticity of the concrete (MPa), ε is the total time-dependent JPCP tensile strain due to shrinkage and thermal effects (-), R is a relaxation factor (viscoelastic JPCP behaviour) (-), and g is an enlargement factor (-).

$$g = \frac{h}{h - jd} \tag{2}$$

The greatest tensile stresses occur at the joints, where a weakened cross-section is present. The concrete thickness below the joint is h-jd (mm), where h (mm) is the thickness of the pavement and jd (mm) is the depth of the transverse joint.

The coefficient of thermal expansion is modelled as a function of the modulus of elasticity, and the hydration temperature is modelled as a function of time. When different expressions of relaxation factors were applied to real-world JPCP scenarios, significant differences were observed. Accordingly, Pradena and Houben proposed a new equation for the relaxation factor, where it is considered as a function of time [20]. The model based on the proposed equation of relaxation was calibrated for traditional JPCPs [19, 20].

In this system approach, the mutual distance between the primary cracks is determined by the so-called breathing length (L_{a1}) (Figure 1). This distance establishes the joints where the 1st series of cracks are produced and how the cracking process will develop.

$$L_{a1}(t) = \frac{E_{cm}(t) \cdot \varepsilon(t)}{\gamma \cdot f} \tag{3}$$

where $E_{cm}(t)$ is the modulus of elasticity (MPa) at the moment of the cracks, $\varepsilon(t)$ is the maximum total obstructed deformation of the pavement at the moment of the primary cracks (-), γ is the volume weight of the concrete (kN/m^3), and f is the friction between the concrete slab and the underlying base (-). Houben [17, 18] assumed a value of 1.0 for the friction of a granular base, which is similar to the value applied in different investigations regarding JPCPs, such as the FHWA model [27, 28], the AASHTO model [26], and the investigations into uncracked joints by Lee and Stoffels [29] and Beom and Lee [30].

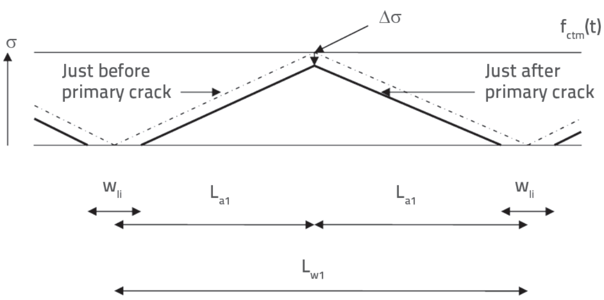

Figure 1. Tensile stresses in the concrete pavement at the time of the primary crack [17, 21]

In this approach, the calculation of the initiation and development of the cracking process in JPCPs considers the pavement as a system with pre-defined weakened sections (joint locations). In this system, the value of the crack width depends not only on the changes in material but also on the locations of the 1st series of cracks, the 2nd series of cracks, and so on until the cracking process is completed. In particular, it depends on the location of the 1st series of cracks and how the cracking process actually develops. For instance, Figure 2 shows that when the 1st series of transverse cracks occurs at every 3rd joint (at the joints nr. 1, nr. 4, nr. 7, etc.), for reasons of symmetry, the possible 2nd series of cracks then occurs together in the two joints lying in between (nrs. 2 and 3, nrs. 5 and 6, nrs. 8 and 9, etc.).
The model was originally developed for traditional JPCPs with enough length to develop the cracking pattern, considering continuity of the pavement structure at the beginning and end of the test section.
The climatic conditions are modelled using the changes in temperature that cause thermal deformation of the pavement. The average temperature between May 1 and November 1 is considered, and the amplitude of the average daily temperature ($T_{ampyear}$) is described using a sine function. The daily temperature of the JPCP is estimated to be a maximum of approximately 25 °C during midsummer (August 1) and a minimum of approximately 5 °C during midwinter (February 1), referring to the northern hemisphere. The amplitude of the daily temperature variation (T_{ampday}) is described using a sine function that reaches its maximum at 4:00 PM, its minimum at 4:00 AM, and its average at 10:00 AM and 10:00 PM [17, 18].
Even when the complex process of JPCP cracking was simplified, the model was calibrated by comparing the results of the modelled crack width with actual ones in Belgian and Chilean JPCPs. As mentioned before, the model has been calibrated for traditional JPCPs [19, 20]. In addition, the model has been applied by Xuan [31], Mbaraga [32], and Wu [33] in their investigations. Xuan [31] analysed the cracking process of cement-treated mix granulates with recycled concrete and masonry for use in pavement bases in the Netherlands. Mbaraga [32] in South Africa and Wu [33] in the Netherlands had similar applications. They applied the model to analyse the cracking process of cement stabilised bases.

3. Methodology

3.1. Significant (and practical) value of the crack width at joints

As mentioned in the introduction, the direct cause of the provision of LTE in non-dowelled JPCPs (as short slabs) is the aggregate interlock depending on the crack width under the transverse joints of the pavement. As a result, a significant (and practical) value of crack width at joints must be defined in order to improve the definition of LTE to be included in the structural design of short slabs JPCPs. This definition must consider that a "good" model depends on what it is used for, i.e., the intended use of the model [34]. The average crack width is a representative value, useful to improve the selection of the LTE to be included in the structural design of short slab JPCPs. Further, as the design is controlled by the widest cracks, the average crack width of the 1st series of cracks (AvCW1st) is the specific one to be considered, because the cracks produced first at the JPCPs are actually the widest ones [17, 18]. Figure 3 shows the link provided by the AvCW1st between the early-age concrete behaviour and the in-service JPCPs. In particular, at the present study the structural performance of the in-service pavement is the one of interest.

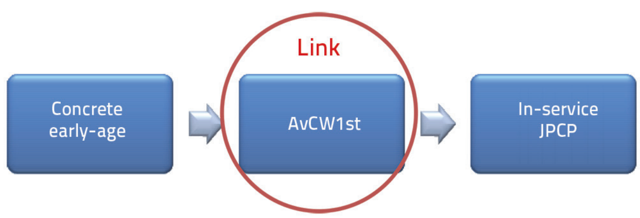

Figure 3. Link provided by the AvCW1st [19]

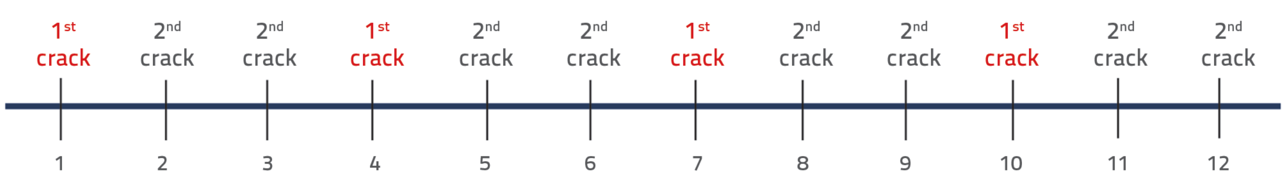

Figure 2. Development of the cracking process when the 1st series of cracks occur every 3rd joint [19]

3.2. Field measurements

Several studies on JPCPs and continuously reinforced concrete pavements have performed crack width measurements [29, 35-39]. Chou et al. [38] measured the crack width corresponding to the midpoint of the thickness (at the pavement edge) in airport JPCPs, although such JPCPs are thicker than those used in other applications. Chou et al. [38] had followed the work of Pitman [36], who performed a statistical analysis of pavement cores and concluded that the crack widths of the upper half were statistically equal to those of the lower half of the cores. Lee and Stoffels [29] performed measurements on the surface of the joints, considering that the surface represents the variation of the crack width along the joint depth. Their decision to perform the measurements on the surface was based on the maximum difference (0.15 mm) reported by Poblete et al. [37] for Chilean undowelled JPCPs; this maximum difference represents less than 5 % of the range of crack width in most cases. Lee and Stoffels [29] considered this difference insignificant for the purposes of their research (analysis of the performance of joint seals). The preceding examples demonstrate the importance of considering the study's objectives when developing an optimal method for measuring crack width at JPCP joints. Accordingly, for the objective of this study and the intended use of the model (AvCW1st for the link with the in-service JPCP performance), performing the measurements of the crack width at the midpoint of the JPCP thickness (at the edge of the pavement) using a fissuremeter (Figure 4) is considered appropriate.

The average pavement temperature is estimated from the information of the meteorological station closest to the JPCP, supported by discrete measurements of the pavement temperature that are obtained using infrared thermometers (Figure 4, right). With this information, the variables $T_{ampyear}$ and T_{ampday} used in the modelling (section 2) are determined with the objective of comparing the modelling results with the real-world JPCP behaviour.

In addition to the crack width measurements performed with the fissuremeter, measurements using a linear variable differential transformer (LVDT) and an invar bar (due to its low coefficient of thermal expansion, $1.2{*}10^{-6}/°C$) were performed. The measurements with the fissuremeter yielded the absolute value of the crack width, and the LVDT (Figure 5) yielded the variation of the crack width at different temperatures. These values were compared with the calculation results of AvCW1st. The LVDT was set up with the bar for each measurement of the variation in crack width (Figure 5 left), and then the LVDT was positioned on two studs that were previously fixed on the edge of the pavement (Figure 5 right).

Figure 4. Measurement of the crack width with a fissuremeter (left) and pavement temperature measured with an infrared thermometer (right) [19]

Figure 5. Measurements with LVDT and invar bar [19]

The LVDT–invar bar system has different practical advantages because the measurements do not require the placement of sensors in the pavement during the construction process. Furthermore, the pavement surface need not be disrupted. The method has an accuracy of 0.001 mm and is cost-effective as only one LVDT is needed for the field measurements. A Sylvac 305-1301 LVDT (Figure 5) was used in this study.

3.3. Comparison of model results with the AvCW1st of real-world short slabs

The model was originally developed (and calibrated) for traditional JPCPs that are sufficiently long for the development of a cracking pattern, with continuity of the pavement structure at the beginning and end of the test section [17-19]. In this study, the model results are compared with AvCW1st values of real-world urban, interurban, and industrial JPCPs with short slabs. Short slabs with continuity of the pavement structure (and enough length for the cracking pattern to develop), as well as test sections with limited length were also included in the comparison.

4. Results

4.1. Urban JPCPs with short slabs

JPCPs that have been traditionally used for model calibration have continuity of the pavement structure at the beginning and end of the test section and sufficient length for the development of a cracking pattern. These conditions have been considered in the originally developed model. However, in cities, it is possible to find JPCPs with different features. Table 1 specifies details of test sections of small streets known as 'cul-de-sac' or dead-end roads located in the Province of 'Bio Bio', Chile.

Table 2 presents the AvCW1st results obtained from field tests and modelling ($T_{ampyear}$ = 10 °C and T_{ampday} = 6 °C). It can be observed that the model is able to predict real-world AvCW1st.

The AvCW1st value of the short-slab section was calculated using the model with a 50% crack width (0.24 mm) of a traditional JPCP that has twice the slab length (0.48 mm crack width for a slab length of 3.50 m). This reduction was based on the work of AASHTO (1993) and NCHRP (2003). The AvCW1st values obtained from the field tests using the traditional JPCP (0.46 mm) and the short-slab JPCPs (0.23 mm) with a 50% slab length, i.e. 3.50 m for the traditional JPCP and 1.75 m for the short-slab JPCP confirmed the results. As these test sections correspond to two adjacent streets in a residential area, they have the same characteristics (Table 1) except for the slab length; the test sections were built under the same climatic conditions and time of day.

4.2. Interurban JPCPs with short slabs

Test sections 'Interurban 1' and 'Interurban 2' of Table 3 are part of an interurban short-slab JPCP located in the Province

Table 1. Characteristics of urban test sections

Test section	**Length section** [m]	**Thickness** [mm]	**RJD*** [%]	**Slab length** [m]	**Base**	**Concrete grade**
Urban traditional	70	120	30	3.50	Granular	C28/35
Urban short slabs	70	120	30	1.75	Granular	C28/35

(*) RJD: Ratio between the saw-cutting depth and the slab thickness. Although Table 1 includes information of the slab thickness, the modelling depends on the RJD.

Table 2. Comparison of real-world and modelled AvCW1st values at the urban test sections

Test section	**Time** [hrs]	**AvCW1st** [mm]	
		Field	**Model**
Urban traditional	60	0.46	0.48
Urban short slabs	60	0.23	0.24

Figure 6. Paving with slipformer (left) and (early-entry) saw-cutting of the transverse joints (right) at the interurban JPCP with short slabs [19]

Table 3. Characteristics of the interurban test sections

Test section	Length section [m]	Thickness [mm]	RJD* [%]	Slab length [m]	Base	Concrete grade
Interurban 1	100	140	35	2.00	Zrnati	C35/45.
Interurban 2	100	140	35	2.00	Zrnati	C35/45.
(*) Includes synthetic fibres type Barcship-54 (2.5 Kg/m^3 of concrete)						

Table 4. Comparison of real-world AvCW1st and modelled AvCW1st at the interurban test sections

Test section	Time [hrs]	AvCW1st [mm]	
		Field	Model
Interurban 1	80	0.20	0.22
Interurban 2	70	0.25	0.23

of 'Tierra del Fuego', Chile (Figure 6). Table 3 presents the characteristics of the test sections. Table 4 presents the results of the real-world AvCW1st values and the values obtained from modelling ($T_{ampyear}$ = 10 °C and T_{ampday} = 6 °C).
Table 4 shows similar results of the real-world AvCW1st values and the values predicted by the calibrated model.

4.3. Industrial JPCPs short slabs

JPCPs in industrial facilities, such as industrial floors and yards, can present length restrictions due to the layout of the industrial complex, warehouse dimensions, discontinuities, etc. As mentioned, the originally developed model does not account for these conditions. Hence, it is important to compare the AvCW1st values predicted by the model with the real-world values. In particular, the test sections 'Industrial 1' and 'Industrial 2' (Table 5) are considered. In effect, these test sections have a length of only 24 m. The rest of the characteristics of 'Industrial 1' and 'Industrial 2' are listed in Table 5.
Figure 7 shows the industrial floor where "Industrial 1" and "Industrial 2" are located (Province 'Concepción', Chile). The figure on the left presents an example of the discontinuities in the industrial floor caused by the industrial layout. Such a configuration results in short JPCP sections.
Table 6 presents AvCW1st values obtained from the field tests and modelling ($T_{ampyear}$ = 10 °C and T_{ampday} = 5 °C). Again, it can be observed that values predicted by the model are close to real-world AvCW1st values.

Table 5. Characteristics of the industrial test sections

Test section	Length section [m]	Thickness [mm]	RJD [%]	Slab length [m]	Base	Concrete grade
Industrial 1	24	120	25	2,00	Zrnati	C28/35
Industrial 2	24	120	25	2,00	Zrnati	C28/35

Figure 7. Construction of industrial floor with shorter irregular sections (left) and general view of the industrial floor (right) [19]

Table 6. Comparison of real-world and modelled AvCW1st values at the industrial test sections

Test section	Time [hrs]	AvCW1st [mm]	
		Field	Model
Industrial 1	72	0.52	0.50
Industrial 2	216	0.58	0.54

5. Implications for the structural design of JPCPs with short slabs

Using dimensional analysis [40], Salsilli et al. [41] developed a practical mechanistic-empirical design method for short slabs that could be used by practitioners. The importance of conducting specific studies of LTE in non-dowelled short slabs was recognised. Pradena and Houben [16] determined the relationship between the load transfer and crack width (at joints) specifically for non-dowelled short-slab concrete pavements. However, the generation of the crack width, i.e. from the early-age concrete behaviour, in short-slab JPCPs was not modelled.

Considering the results presented in this article, which indicate the accuracy of the crack width predictions (at joints) of real-world short-slab JPCPs, it is possible to account for the direct cause of the LTE, i.e. the crack width at joints produced at an early age, in the structural design of short slabs.

Figure 8 shows the variables included in the modelling of early-age concrete behaviour. The main output of the modelling process is the crack width at joints, which can be used as the input for obtaining the LTE directly from its cause (the aggregate interlock).

Thus, with the validated model for short-slab JPCPs, the LTE can be related to the direct cause instead of indirect causes (such as temperature) that are sometimes used to create relationships with the LTE of the in-service JPCP (Figure 8). The direct definition of LTE is fundamental in the design of short concrete slabs, which will help maintain one of the main characteristics of concrete pavements, i.e. their durability [42].

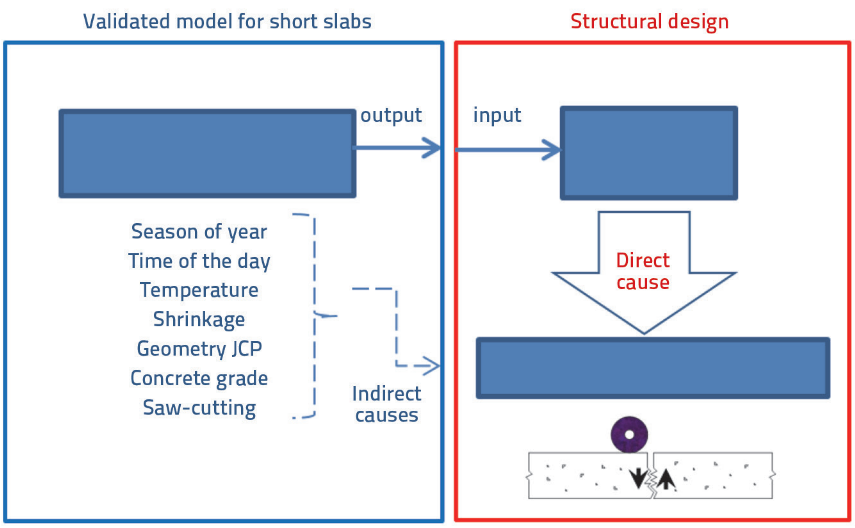

Figure 8. Implications of the validated model of the early-age concrete behaviour on the structural design of short-slab JPCPs (Adapted from Pradena and Houben [16])

6. Conclusion

In this study, a model developed for the prediction of the crack width at joints in traditional JPCPs was calibrated and validated for short-slab JPCPs. The modelling results were compared with the crack width of real-world short slabs of urban, interurban, and industrial JPCPs with different configurations as well as limited length. This modelling enables the incorporation of the direct cause of the LTE by aggregate interlock as the crack width at joints produced since an early age in the structural design of short-slab JPCPs. The model considers different variables (pavement temperature, shrinkage, concrete grade, geometry of the pavement, saw-cutting, season of the year, and time of the day when the pavement is constructed, among others) in a system approach instead of fixed mean values as in the AASHTO formula. Finally, using the validated model for short-slab JPCPs, the LTE can be related to the direct cause rather than indirect causes (such as temperature) that are sometimes used to create relationships with the LTE of in-service JPCPs. However, they do not relate the LTE by aggregate interlock with the direct cause; this was addressed in the present study.

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