ANALYSIS OF STRESS RELAXATION IN JOINTED PLAIN CONCRETE PAVEMENTS

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Abstract. The cracks in concrete pavements are formed at early-age as consequence of internal stresses in the concrete. Therefore, the stress relaxation has an essential influence on the cracking process. To model this process allows to identify, for instance, the time for saw-cutting the joints or the cracks width that affects load transfer. Previously, the authors proposed a new equation of the relaxation factor, based on a theoretical and practical analysis of the transversal cracking in jointed plain concrete pavements. The objective of the present paper is to analyze the utility of this new equation of relaxation in the design and construction of jointed plain concrete pavements. For that, other cracking processes in plain concrete pavements (jointed and non-jointed) were modelled with the proposed equation. Wherever is possible the modelling results were compared with observations of the real behaviour of pavements. From the design point of view, with the modelling results of transverse crack width (>1.0 mm) is possible to considerate in the design, optimal slabs length with thinner cracks for better aggregate interlock. And for the longitudinal cracking in jointed plain concrete pavements, the modelling and the field observations, yield cracks width that provide load transfer (<0.1 mm). From the construction point of view, the cracking process in non-jointed plain concrete pavements, shows is possible to construct pavements of 7 m width in one gang without cracks risk, and adjustments can be made to a better prediction of the time of occurrence of the 1st transverse cracks.

Keywords: stress relaxation, model, jointed plain concrete pavements, cracking, saw-cut, load transfer.

1. Introduction

Concrete has a characteristic visco-elastic behaviour. The relaxation is the time-dependent stress reduction, induced by a constant sustained deformation. As the cracks in concrete pavements are formed at early-age, the stress relaxation has an essential influence on the cracking process of concrete pavements. The modelling of the cracking process is important to knowing fundamental variables of the design and construction of Jointed Plain Concrete Pavements (JPCPs), for instance the cracks width that affects load transfer in JPCPs and the time for saw-cutting the joints.

In fact, the development of the crack width affects the load transfer between slabs. A low load transfer increases the deterioration and the risk of structural failure. But wider cracks also contribute to other types of deterioration like spalling and joint faulting that affects pavement unevenness (IRI – value). That means less comfort for the road user and a higher rate of deterioration on the pavement. The effect is bigger in pavements without dowels bars. Hence, knowing one of the main results of the modelling since early-age, the crack width, is possible to control the variables involve in the process of cracking in order to obtaining narrower cracks width to a better structural and functional behaviour of the JPCPs. Crack control is also often the governing design criterion for the choice of the amount of longitudinal reinforcement in continuously reinforced concrete pavements and prestressing of reinforced concrete bridges. In JPCPs crack control allows, for instance, to design the pavement with an optimal slab length or to define the minimum relative joints depth (ratio of saw-cut depth and concrete thickness).

Houben (2010a, 2010b) has developed models concerning the transversal cracking in concrete pavements using equations from the standard *NEN-EN 1992-1-1:2005 Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings (in Dutch)*, for the time-dependent concrete properties and the drying and autogenous shrinkage. For properties that are not available in standards, Houben made assumptions based on engineering judgment. After that, the authors studied

those assumptions more in depth, considering the model of Zhan and Li (2001) for the friction between the concrete slab and the base, the calculation of the hydration temperature using *HYMOSTRUC* software (Ye *et al.* 2007), and the relaxation models of Morimoto and Koyanagi (1995) and Lokhorst (2001). As a result, the authors made a proposal for a new relaxation factor based on theoretical and practical analysis of the transversal cracking process in JPCPs. In that analysis, comparisons were made with preliminary field measurements on JPCPs in Belgium and Chile (Pradena, Houben 2012a).

In this present contribution the objective is to analyse the utility of this new equation of relaxation in the design and construction of JPCPs. For that, other processes of cracking in JPCPs and Plain Concrete Pavements (PCPs) are modelled with the proposed equation of relaxation. These cracking processes are; the transversal cracking of PCPs and the longitudinal cracking of both, JPCPs and PCPs. Wherever is possible the results of the modelling are compared with observations of the behaviour of JPCPs. For instance, in PCPs (*i.e.* non-jointed) field measurements are improbable because the observations would require a "wild" cracked pavement. Then, the results of modelling are compared with new field observations of the cracks under transverse and longitudinal joints of JPCPs.

2. Methods

2.1. Practical approach of the analysis

The prediction of the cracking process in JPCPs is a very challenging subject. In particular, to obtain the expression of the relaxation since early-age directly from laboratory tests have been found difficult. And, due to this lack of experimental data on stress relaxation at early- ages most of the theoretical studies on self-induced stresses use creep properties for modelling (Atrushi 2003). However, stress relaxation (and not creep) is involved directly in reduction of self-induced stresses in hardening concrete (Atrushi 2003). As this paper deals with the challenging subject of the prediction of the cracking process in JPCPs, and because similar difficulties were found in relaxation tests at Delft University of Technology, in the present analysis a practical approach has been considered to the particular case of JPCPs. In fact, JPCPs are concrete structures with special characteristics that need to be taken into account in the modelling process in order to find realistic results. In JPCPs, for instance, the concrete layer is part of a layered pavement system subjected to varying (climatic) conditions.

Related with the objective of this contribution, the practical approach consists in a design-performance approach and a construction approach.

2.1.1. Design-performance approach

The design-performance approach is associated with the cracking process under the joints of JPCPs. In fact, the cracks width under the joints affects the structural and functional deterioration of JPCPs, because the crack width is related with the Load Transfer Efficiency (LTE) between slabs, especially in undowelled JPCPs where basically the aggregate interlock transfers the load. In undowelled JPCPs, a LTE 70% or higher is generally considered appropriate to a good performance. A crack width of 1.0 mm or less provides this appropriate LTE, according to the experimental verification of the joint load transfer of the finite-element software EverFE (Davids, Mahoney 1999). A low LTE accelerates the structural and functional deteriorations on JPCPs, for instance cracks in the slabs, joint faulting, higher values of roughness and even deflection spall. Hence, knowing the cracks width under the joints is fundamental for the design of the pavement and the performance of JPCPs, especially when no dowel bars are applied (which is common practice in Chile for instance). In the design of JPCPs, cracks control allows to find slabs length with thinner cracks width at joints.

Accordingly, for the design-performance approach the useful outputs of the modelling at early-age are the ones to linking the effect of the concrete behaviour at that age with the performance of JPCPs. From this point of view, the realistic outputs of the modelling at early-age are trends in agreement with the reality more than exact values (for instance, values of cracks width possible to linking with LTE). The trends are quantified by the average crack width, because the average crack width is a representative value, useful to linking with the average LTE through the life cycle of the pavement. Because the design is controlled by the widest cracks, the average crack width of the 1st series of cracks is the one to be considered in the practical approach. Then, this is the value of interest for the modelling and the field observations. In particular, the average value after 1 year of the JPCPs in service, because it remains more stable during the performance of the JPCPs (Houben 2010b). Consequently, is this average value of the crack width of the 1st series of cracks, the one analyzed taking into account the limit of 1.0 mm for the provision of LTE by aggregate interlock.

The field observations were made from this practical approach. For the case of the transversal cracking process at joints, new field measurements were made in JPCPs sections of 100 m length at the Province of Concepcion in Chile (4 m joint spacing), and at the Province of Limburg in Belgium (5.5 m joint spacing), slabs width 3.5 m, relative joints depth 30% and similar climatic conditions (described later in Table 2). According to Houben (2010b) the average crack width after 1 year, i.e. the crack width related with the performance of the JPCPs, does not change significantly for the range of the slab lengths of 3.75 m to 6.0 m. Hence, the differences in the joint spacing of the Chilean sections and the Belgian one were not considered significant. For instance, field observations were made in Chile, at January 2012, in the Province of Concepcion for the transversal joints (Fig. 1) and in the Province of Tierra del Fuego for the longitudinal joints (Fig. 2). Upper right in the picture is possible to observe the amplification of the crack.

Fig. 1. Crack under transverse joint in JPCP, Province of Concepcion. 8:00 am – temperature at the surface of the pavement 13 °C

Fig. 2. Crack under longitudinal joint in JPCP (7 m width), Tierra del Fuego Province. 2:00 am – temperature at the surface of the pavement 10 °C
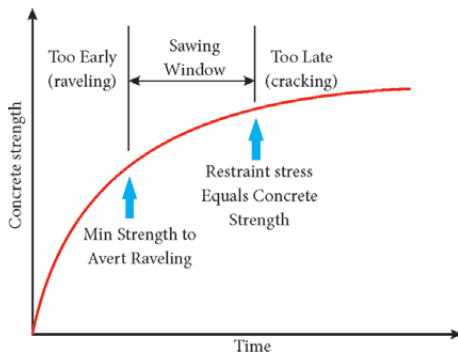
Fig. 3. Sawing window (Okamoto *et al.* 1994)

All the JPCPs considered in this contribution were built at the hottest moment of the year. In general the construction of JPCPs at that moment of the year represents the most unfavorable conditions for the design of the pavement (widest cracks).

The Chilean sections for transversal cracking were built with traditional construction method of JPCPs, i.e. vibrating beam over fixed formwork. The Belgian section and the Chilean JPCP for longitudinal cracking were built with slipformpaver.

2.1.2. Construction approach

The time of occurrence of the 1st series of cracks determines the time available to perform the saw-cutting before the "wild" cracking of the JPCPs (Fig. 3). This information is important for the efficient use of the equipments and staff for saw-cutting the joints, in order to assure a good result of the construction process.

Field measurements at PCPs are highly improbable because the observations would require a "wild" cracked pavement. Then, the modelling results are compared with the time of occurrence of undesirables "wild" cracks observed in JPCPs practice. These problems in projects require pavement reparations and extra costs; hence this is information not easy to publish. Therefore, the general practice observed through the years by the authors is considered in the practical construction approach.

2.2. Models of cracking process

In this section a brief description of the individual models is given. The Table 1 shows as a summary the approaches to the modelling made by Houben (2010a, 2010b) and by Pradena and Houben (2012a).

The time-dependent stress $s(t)$, occurring in the transverse direction of a non-jointed plain concrete pavement due to the total obstructed deformation $\varepsilon(t)$, follows from Hooke's law. Because of the semi-static loading, however, also stress relaxation is taken into account. This leads to the following equation:

Table 1. Summary of the Houben approach and the Pradena and Houben approach

Variables	Houben approach	Pradena and Houben approach
Friction	$L_{a1} = \dfrac{E_{cm}\varepsilon}{\gamma f}$	$\dfrac{d^2 u}{dx^2} - \dfrac{\tau}{Eh} = 0$
Hydration temperature	$T_h = t^2 e^{-0.27t}$	$T_h = \dfrac{m_c Q}{d_c c_c}$
Coefficient of thermal expansion	$CTE = 3.095 \cdot 10^{-10} E$	Different expressions
Strength and elastic modulus	*Eurocode 2*	*Eurocode 2 + t_e* (maturity method)

where L_{a1} – breathing length, m; E_{cm} – average modulus of elasticity, at the moment of the crack, MPa; ε – max total obstructed deformation of the plain concrete pavement; γ – volume weight of the plain concrete pavement, kN/m³; f – friction between the plain concrete pavement and the underlying base; τ – slab-base interfacial friction, MPa; u – average displacement through the JPCP slab thickness, mm; E – elastic modulus of concrete, MPa; h – height of the slab, mm; T_h – hydration temperature, ºC; t – time after construction of concrete pavement, h; m_c – mass of the cement per m³ of concrete, kg; Q – hydration heat released till time t, kc/kg; d_c – density of concrete, kg/m³; c_c – specific heat of concrete, kc/kg ºC⁻¹; CTE – coefficient of thermal expansion at time t, ºC⁻¹; t_e – equivalent age at reference curing temperature, h.

$$\sigma(t) = RE_{cm}(t)\varepsilon(t), \text{ MPa}, \tag{1}$$

where R – stress relaxation factor.

In the transverse direction of the concrete pavement the breathing length L_{a1W} is limited to max half of the width W as constructed by the slipformpaver in one gang:

$$L_{a1W} = MIN\left(L_{a1\infty}, \frac{W}{2}\right), \text{ m}, \tag{2}$$

where MIN – minimum value.

In the case that there is 1 longitudinal joint in the centre of the pavement, the occurring tensile (or compression) stress s(t) is always max at the joint because of the reduced cross section at that location. The occurring tensile (or compression) transverse stress $\sigma_j(t)$ at the longitudinal joint is equal to:

$$\sigma_j(t) = \frac{100}{100 - rjd}\sigma(t) = g\sigma(t), \text{ MPa}, \tag{3}$$

where s(t) – stress in centre of pavement if there would not be a longitudinal joint (Eq (1)); rjd – relative joint depth (ratio of saw-cut depth and concrete thickness), %; g – enlargement factor for stress at longitudinal joint relative to stress in full cross section (without longitudinal joint).

The occurring tensile (or compressive) stress s(t) in the transverse direction at the location of the central longitudinal joint is limited according to:

$$-\gamma f \frac{W}{2} \frac{100}{100 - rjd} R \leq \sigma_j(t) \leq \gamma f \frac{W}{2} \frac{100}{100 - rjd} R, \text{ MPa}. \tag{4}$$

The alternative approach for the modelling of the independent variables improves the theoretical background, but it does not produce significant changes of the behaviour of the pavement, with the exception of the relaxation factor. Hence, in the present work the Houben model (2010a, 2010b) is applied with the exception of the relaxation factor.

2.3. The relaxation factor

The modelling of the stress relaxation is a very challenging subject. In particular, to obtain the expression of the relaxation since early-age directly from laboratory tests have been found difficult. For that, in general the researchers have made theoretical studies on self-induced stresses use creep properties for modelling (Atrushi 2003). However, stress relaxation (and not creep) is involved directly in reduction of self-induced stresses in hardening concrete (Atrushi 2003). In fact, Pradena and Houben (2012a) found significant differences in the results obtained for the relaxation models of Morimoto and Koyanagi (1995), Lokhorst (2001) and Houben (2010a), when they were applied to real situations of JPCPs. The expression proposed by Houben (2010a) was the only one with realistic results but calculation results (crack widths) are smaller than the ones observed in practice during preliminary field measurements in Belgium and Chile. Considering these results, the fact there is a lack of experimental data on stress relaxation at

early-ages, and the importance of stress relaxation in the reduction of self-induced stresses in hardening concrete, Pradena and Houben (2012a) proposed the Eq (5) for the relaxation factor as a function of the time, based on a theoretical and practical analysis of the transversal cracking in JPCPs.

$$R = 0.8265e^{-8\cdot10^{-5}t}. \tag{5}$$

The Fig. 4 shows different expressions of the relaxation factor including the proposed Eq (5) of Pradena and Houben (2012a).

2.4. Simulation conditions of cracking process in JPCPs and PCPs

The Table 2 shows the parameters that were kept constant in all the cases analysed in this paper.

The climate-dependent temperature has been modelled as a sine function, taking into account the yearly temperature amplitude ($T_{ampyear}$) and the daily temperature amplitude (T_{ampday}).

The friction between the concrete pavement and the underlying base is a combination of the coefficient of friction and the dead weight of the concrete slab (Houben 2010a).

The terminology hottest moment of the year, refers to the day or days when the temperature is highest in a certain location. In general, the construction of JPCPs at this moment of the year represents the most unfavorable conditions (widest cracks). In this evaluation a max temperature of 30 °C has been considered. It results from a sinusoidal average temperature of 15 °C and the Tampyear and Tampday indicated in Table 2. In the Netherlands, for instance, the maximum temperature is produced at the beginning of August.
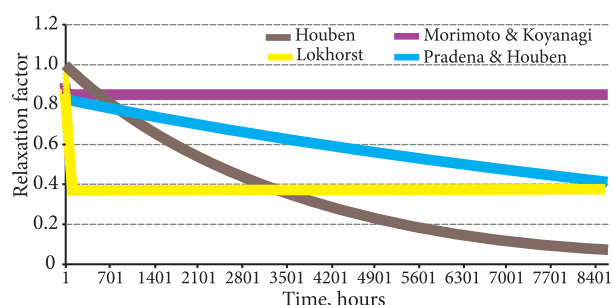

Fig. 4. Different expressions of the relaxation factor

Table 2. Constant parameters in the simulations

Parameter	Data
Period of evaluation	8640 h (≈ 1 year)
Yearly temperature amplitude	10 °C
Daily temperature amplitude	5 °C
Concrete grade	C28/35
Time of construction	hottest moment of the year
Friction	1

The conditions of the simulation to the transversal cracking process in JPCPs are; transverse joint spacing 4.5 m, and joint depth 30%.

The simulation conditions of the longitudinal cracking process in JPCPs are; pavement width 3 m, 6 m, 9 m; 1 longitudinal joint, and joint depth 25%.

The conditions of the simulation to the longitudinal cracking process in PCPs are; pavement width 3 m, 6 m, 9 m.

3. Results

3.1. Cracking under joints of JPCPs

For the design-performance approach the useful outputs of the modelling at early-age are the ones to linking the effect of the concrete behaviour at that age with the performance of JPCPs. For that, the average crack width of the 1st series of cracks is appropriate, taking into account the limit of 1.0 mm for the provision of LTE by aggregate interlock. Table 3 presents a summary of the results of field measurements of transversal cracking made in the JPCPs sections of Belgium and Chile. The comparison with the model has been made with the average width of the 1st series of cracks, because they are the widest ones, and thus the most critical to the behaviour on medium and long term of the pavement. Although when from the practical approach, the value to be considered is the average crack width of the 1st series of cracks after 1 year, a comparison is made at early-age as well to contrast the model at that time.

The model yields similar values of the average width of the 1st series of transverse cracks observed in practice at different ages. In particular at early age, when all the changes are developing in the concrete, and after 1 year when the behaviour of the crack width is more stable, and then

Table 3. Comparison between the model and field measurement results

JPCP section	Age	Average crack width 1st series of cracks, mm	
		Field measurements	Model
Section 1 – Chile	72 h	1.2	1.0
Section 2 – Chile	504 h	1.2	1.2
Section 3 – Belgium	>1 year	1.8	2.1
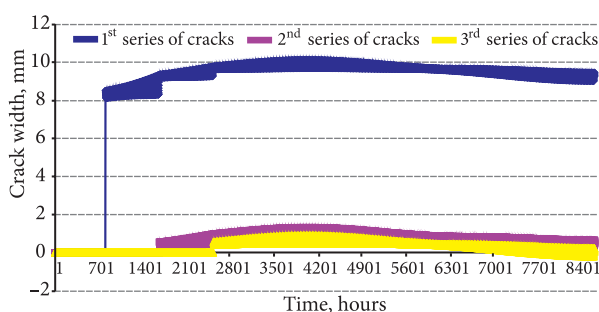
Fig. 5. Development of transverse cracks width during 1 year

it is possible to relate with the behaviour on medium and long term of the pavement.

In the case of the longitudinal joints of JPCPs, no cracks occur in any width (3 m, 6 m, and 9 m).

3.2. Cracking at PCPs

The Fig. 5 presents the development of the transverse cracks width during 1 year. Three series of cracks are produced and the final crack spacing is about 40 m. As the field measurements for the study of the cracking in PCPs are highly improbable, the attention needs to be focussed in the time of occurrence of the first cracks. The model yields a time of occurrence of 810 h for the 1st series of cracks.

In the case of potential longitudinal cracking of PCPs, no cracks occur in any width (3 m, 6 m, and 9 m).

4. Analysis and discussion

4.1. Design-performance approach

In the case of the transversal cracking process at joints the new field measurements made in Chile and Belgium confirm the proposed equation of the relaxation factor. Taking into account the limit of 1.0 mm for the provision of load transfer by aggregate interlock and the order of magnitude of the cracks width of the 1st series of cracks, the modelling allows concluding that the cracks width will not be able to provide load transfer for a good performance of the JPCPs.

In the design of JPCPs, cracks control through the modelling allow to obtain slabs length with thinner cracks width at joints. Thus, is possible to consider shorter slabs as an alternative to the traditional ones. In fact, the authors found a reduction of 40% of the average width of the 1st series of cracks in shorts slabs in Chile, with 50% of the traditional slabs length and similar climatic conditions that the JPCPs sections of this paper (Pradena, Houben 2014). In this way, the reduced crack width of shorter slabs provide adequate LTE by aggregate interlock (without dowels bars), and consequently good performance of the JPCPs. The shorts slabs was studied in full-scale test sections constructed and tested under accelerated pavement loading conditions at the University of Illinois' Advanced Transportation Research and Engineering Laboratory. The short slabs had good performance, without dowels bars, and with less thickness than the traditional JPCPs, because of the loads configuration over the pavement (Roesler *et al.* 2012).

As no cracks occur in the analysed cases of the cracking under the longitudinal joints of JPCPs, a new analysis was made with friction values of 5 and 10. With friction 5 a crack was produced for a pavement width 9 m and with friction 10, cracks were produced for pavements widths 6 m and 9 m. In all the cases the crack width under the longitudinal joint never exceeds 0.09 mm (Fig. 6).

Preliminary field measurements made in Chile show a range of cracks width under the longitudinal joints between 0.05 and 0.1 mm after 2000 h, and according to the modelling (Fig. 6) the order of magnitude of the crack width will not change. Hence, in particular for the conditions of

the simulation, the proposed equation of the relaxation factor is useful to predict the longitudinal cracks width related with the design-performance of JPCPs.

With a crack width of the order of magnitude shows in Fig. 6, and taking into account the limit of 1.0 mm for LTE ≥ 70%, enough load transfer by aggregate interlock is expected, and then good behaviour of the JPCPs.

In comparison with the transversal cracking, in the longitudinal case the friction needs to be bigger to produce cracks because the concrete has less restriction to its movement in the transverse direction.

4.2. Construction approach

No longitudinal cracks occur in the analysed cases of the cracking in PCPs. Hence, taking into account a safety factor of 1.25 against the uncontrolled "wild" cracks, is possible to construct a JPCP of 7 m width in one gang, without risk of longitudinal cracks at the first hours. This knowledge is very important because it help to distribute the construction resources in an efficient way, putting the attention in the critical points, as the saw-cut of the transverse joints. In particular, the JPCP of 7 m width at Province of Tierra del Fuego (Chile), was constructed in one gang (average daily production: 700 m of JPCP). During the first hours the attention was put in saw-cutting the transverse joints but not in the longitudinal joints because there was no risk of longitudinal cracks (Pradena, Houben 2012b).

As no longitudinal cracks occur in the analyzed cases of the cracking in PCPs, a new analysis was made with friction values of 5 and 10. In all the cases only 1 longitudinal crack occurs, if any, and the crack width never exceeds 0.3 mm. Cracks occur only in the case of friction 10 and pavement width 6 m and 9 m. The crack always occurs at 12 h after the concrete is poured (4 pm), *i.e.* in the first night. If a safety factor of 1.25 against the uncontrolled "wild" cracks is taken into account, a crack is also produced when the friction is 5 and the pavement width 9 m. In this case if the concrete is poured at 4 pm, the crack is also produced 12 h later, *i.e.* in the first night. Then, in the longitudinal cracking process in PCPs, the times of occurrence of the crack are in agreement with the general construction practice of JPCPs, under similar conditions that the ones taken into account in the simulation (field measurements in this case are highly improbable).

In comparison with the transversal cracking, in the longitudinal case the friction needs to be bigger to produce cracks because the concrete has less restriction to its movement in the transverse direction.

For the case of the transversal cracking process in PCPs, the model yields a time of occurrence of 810 h for the 1st series of cracks. This time is longer than the time available to make the saw-cuts observed in the construction practice of JPCPs. Then, an extra model calculation was made, under *ceteris paribus* condition, considering a T_{ampday} of 10 °C. In this case the time of occurrence of the 1st series of cracks was 16 h after construction, a value closer to the practice of construction of JPCPs.
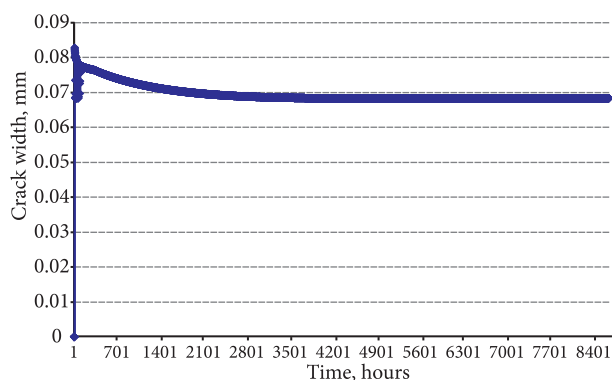

Fig. 6. Development of the longitudinal crack width during 1 year; Friction 5 – pavement width 9 m

4.3. Calibration of the model

Possibilities of adjustments of the model are noted, when the time of occurrence of the 1st series of transverse cracks in PCPs for the general conditions of the simulation (Table 1) are considered. The calibration of the model allows more accurate predictions related with the construction approach, specifically the time to saw-cutting the transverse joints. The possibilities to improve the modelling are performing laboratory tests and field measurements. However, laboratory tests of relaxation at early-age have been found very difficult, and due to this difficulties and lack of experimental data on stress relaxation at early- ages, relationships with the development of creep are commonly used (Atrushi 2003). In relaxation tests at Delft University of Technology similar difficulties were encountered. Nevertheless, stress relaxation (and not creep) is involved directly in reduction of self-induced stresses in hardening concrete (Atrushi 2003).

The field measurements of the cracking process in PCPs are highly improbable, because the observations would require a "wild" cracked pavement. Hence, the adjustments in the model need to be made through field measurements of the longitudinal and transversal cracking process in JPCPs under construction, putting attention in the time of saw-cutting and the time of occurrence of the cracks (when it is possible, for instance in construction with slipformpaver). With this approach, is possible to calibrate the curve for different conditions using the least squares method.

The calibration of the relaxation curve is a practical solution taking into account the difficulties of relaxations tests in the laboratory at early-age, the fact the model has in general a good correlation with field behaviour of JPCPs, and the possibilities of improvements are concentrated at early-age.

5. Conclusions

1. Even if the equation of the relaxation factor varies slightly with some adjustments of the calibration, is possible and useful, to apply this equation in order to obtain valuable information for the design and construction of jointed

plain concrete pavements. This information is obtained modelling the longitudinal and transversal cracking processes in jointed plain concrete pavements and plain concrete pavements.

2. From the design point of view, the modelling yields the magnitude of the crack width related with load transfer efficiency. For the simulations conditions, the aggregate interlock is not able to provide enough load transfer due to the magnitude of the transverse cracks width. With this information is possible, for instance, to design the pavement with optimal slab length. Between other advantages, shorter slabs produce cracks under the joints adequately thinner to provide the aggregate interlock that is fundamental for a good load transfer between slabs. This decision in the design of jointed plain concrete pavements shows the utility of the proposed equation of relaxation. The equation was confirmed with the new field measurements of the transversal cracking process made in Chile and Belgium.

3. From the design point of view as well, the modelling and the field observations yield longitudinal crack width less than 0.1 mm in jointed plain concrete pavements. Consequently, enough load transfer by aggregate interlock is provided, and a good performance of the jointed plain concrete pavements is expected.

4. From the construction point of view, the longitudinal cracking process in plain concrete pavements, shows is possible to construct jointed plain concrete pavements with 7 m width in one gang without cracks risk. And possibilities of adjustments were noted in the time of occurrence of the first transverse cracks in plain concrete pavements.

5. The possibilities to make adjustments to the equation of relaxation are performing laboratory tests and field measurements. However, laboratory tests of the relaxation at early-age have been found very difficult. On the other hand, field measurements of the cracking process in plain concrete pavements are highly improbable, because the observations would require a cracked pavement. As a result, the adjustments in the equation need to be made through field measurements of the cracking process in jointed plain concrete pavements under construction. With this practical approach, is possible to calibrate the relaxation curve for different conditions, using the method of least squares. The calibration of the relaxation curve is a practical solution taking into account the difficulties of the laboratory tests of relaxation, and the fact the model has a general good correlation with the behaviour of jointed plain concrete pavements in field.

Acknowledgements

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