INNOVATIONS IN CONCRETE PAVEMENTS FOR A SUSTAINABLE INFRASTRUCTURE

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Abstract: Concrete pavements (CPs) are durable and they do not need periodic invasive maintenance interventions. Nevertheless, CPs are hardly chosen when only initial costs, instead of life-cycle costs, are considered in the evaluation. Nowadays, there are innovations in Jointed Plain Concrete Pavements (JPCPs) that reduce initial costs about 25% with respect to alternatives with equivalent structural capacity. This paper addresses the question if the innovations early-entry saw-cutting of joints, joints without seals and shorter joint spacing (without dowels bars) are able to maintain the traditional life-cycle performance of CPs. All these innovations affect the joints of the JPCP, and these ones the JPCP performance. Accordingly, the objective of the present paper is to analyse the effects of the joints behaviour on the performance of the JPCPs innovations. The joint behaviour is characterized by the joint activation and opening, and the capacity to transfer traffic loads and the joint deterioration. The calculations of the joints activation and opening are made with a model developed by the authors. For the estimation of the joint transfer capacity; the results of finite-element software are used. The analysis is completed with field data of the JPCPs innovations. The innovations analysed contribute to a sustainable infrastructure as they can maintain, and even improve, the traditional life-cycle performance of CPs with lower initial costs. Nevertheless, for the design hypotheses to be valid, it is necessary to assure the joints activation and to limit the joints opening to 1.2 mm. With this purpose, for the analysed conditions, it is recommended to cut the joints at least at 30% of the JPCP thickness.

Keywords: Innovations, Concrete, Pavements, Sustainable.

1. Introduction

A technical, economic and environmental analysis over the road life cycle shows that Concrete pavements (CPs) are a sustainable paving alternative. In fact, CPs are durable and they do not need periodic invasive maintenance interventions. Nevertheless, CPs are hardly chosen when only initial costs, instead of life-cycle costs, are considered in the evaluation. However, in order to reduce construction costs, nowadays there are JPCPs innovations as Early-Entry Saw-Cutting (EESC) of joints, Joints Without Seals (JWS) and Shorter Joint Spacing (ShJS). The question is, Are these JPCPs innovations able to maintain the traditional favourable life-cycle performance of CPs?. All these innovations affect the joints of the JPCP, and these ones the JPCP performance. Accordingly, the objective of the present paper is to analyse the effects of the joints behaviour on the performance of the JPCPs innovations EESC, JWS and ShJS. The joint behaviour is characterized by the joint activation and opening, the joint capacity to transfer traffic loads and the joint deterioration. The calculations of the joints activation and opening are made with a model developed by the authors. For the estimation of the joint transfer capacity; the results of a finite-element analysis tool are used. The analysis is completed with field data of the JPCPs innovations.

2. Innovation in jointed plain concrete pavements

2.1. Early-Entry Saw-Cutting (EESC) of joints

Early-Entry Saw-Cutting (EESC) consists in a shallow cut (up to 30 mm depth) made with light equipment that allows the saw-cutting 3-5 hours after concrete placement. EESC was introduced to the paving industry in 1988 by a concrete pavement contractor looking for a method to cut the joints shortly after the surface is finished, in order to eliminate the need to return the next day to cut the joints (McGovern, 2002). EESC relieves internal concrete stresses avoiding the "wild" cracking of the pavement and it is postulated that the saw-cut can be shallower at an early age, taking advantage of the significant changes in moisture and temperature conditions at the surface of the slab to help initiate the crack below the saw-cut (Zollinger et al, 1994).

2.2. Short Joint Spacing (ShJS)

When the concrete slabs are designed and constructed such that only one set of truck wheels rest on a single slab, the slab tensile stresses are reduced also because shorter slabs produce less slab curling. This result in thinner concrete pavements (70 to 100 mm less than traditional AASHTO design) (Roesler, 2013) and savings in initial construction costs about 30% (Covarrubias, 2008). Between the pavement design features are: short joint spacing (< 3 m), slab thickness 80 mm to 200 mm; granular base with limited fines (<8% passing 75 µm) and minimum 15 cm thickness; thin saw-cut at joints (2-3 mm thick); no joints sealing; lateral confinement with curb, shoulder or vertical steel pins; no dowel or tie bars (Roesler, 2013).

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2.3. Joints Without Seals (JWS)

The function of the joint seals is keeping the joint free of water and incompressible. The introduction of water can drag fines from the base (pumping), so less support and it could produce JF as well as cracks on the slabs. The coarse incompressible materials in the joint have the potential to produce considerable pressure against the edges of the joint, so spalling or even splitting cracks. The costs of sealing transverse contraction joints it is estimated between 2 and 7 percent of the initial construction cost of a JPCP (Hall, 2009). And when the cost of keeping the joints sealed for 10 years is added, the JPCP with sealed joints ends up costing up to 45% more than the one with unsealed joints (Shober, 1987). The problem is that the joint seals are not working well enough, not keeping the joint free of water and long-term Joint Faulting (JF) data shows a strong correlation with annual rainfall (Jung et al, 2011). In fact, the average service life of the joint seals is less than 10 years. They commonly have adhesive and/or cohesive failures. But also they can suffer from hydraulic pressure from tires (Jung et al, 2011). Considering the problems of the joint seals and their costs, there is increased interest in eliminating joint sealants. The innovation of JWS consists in a saw-cut as narrow as possible and a base with limited fines. In effect, a saw-cut ≤ 3 mm impede the introduction of coarse material in the joint and when the amount of fines in the underlying base/soil layer is limited; the water cannot drag fines, so no pumping, and no production of JF for this concept. The JWS can be applied to JPCPs with traditional slabs or ShJS.

3. Joint behaviour on the performance of CPs innovations

The expectations of the costumer must be considered in the Life Cycle (LC) of the road. For that reason, the design must be studied together with the maintenance, the impacts upon the users and the residual value of the pavement (Pradena and Echaveguren, 2008). Therefore, the evaluation needs to consider the effect of the joint performance on the JPCP performance, so at the end upon the users and the costs. For instance, JF is the major contributor to the JPCP’s roughness, and joint spalling could increase it as well. In this paper the JPCP roughness is quantified by the International Roughness Index (IRI) and the joint behaviour is characterized by the joint activation and opening, the joint capacity to transfer traffic loads and the joint deterioration.

3.1. Joint activation and opening

The calculations of the joints activation and opening are made with a model developed by the authors. In this section a brief description of the model is made, more details can be found in the work of Houben (2010a, 2010b) and Pradena and Houben (2012). In the JPCP, the occurring tensile stresses as a product of the restricted deformation follow from Hooke’s law, but they are affected by the viscoelastic behaviour of the concrete (relaxation) (Houben, 2010a).

\[ \sigma(t) = g \cdot R \cdot E(t) \cdot \varepsilon(t) \]  

(MPa)

where \( E(t) \) = time-dependent modulus of elasticity of the concrete (MPa); \( \varepsilon(t) \) = total time-dependent JPCP tensile strain due to shrinkage and thermal effects (-); \( R \) = relaxation factor (viscoelastic JPCP behaviour) (-); \( g \) = enlargement factor (-)

\[ g = \frac{h}{h - jd} \]  

(-)

The greatest tensile stresses occur in those weakened cross-section. When the JPCPs thickness is \( h \) (mm) and the saw-cut depth \( jd \) (mm), the relative joint depth \( rjd \) is:

\[ rjd = \frac{jd}{h} \times 100 \]  

(\%)

The tensile stresses build up over the so-called breathing length (\( L_{bat} \)). This is that part of a long structure that exhibits horizontal movements due to temperature changes (or another varying influencing factor) (Houben 2010b).

\[ L_{bat} = \frac{E_{cm} \cdot E}{\gamma \cdot f} \]  

(m)

Where \( E_{cm} \) = average modulus of elasticity (MPa) at the moment of the crack; \( E \) = maximum total obstructed deformation of the pavement (-); \( \gamma \) = volume weight of the concrete (kN/m\(^3\)); \( f \) = friction between the concrete slab and the underlying base (-).
The cracks occur when the tensile stress ($\sigma$) exceeds the tensile strength ($f_{ctm}$). Because of the initial crack width $w_{i1}$, a reduction $\Delta \sigma_1$ of the maximum tensile stress occurs. The spacing $L_{w1}$ between 2 primary cracks is equal to 2 times the breathing length.

![Diagram showing crack development and stress distribution](Image)

**Fig. 1.**
Development of the tensile stresses and cracks initiation in the pavement
Source: Houben, 2010b

Eq. 5 allows the calculation of the initial crack width $w_{i1}$ of the first occurring primary cracks.

$$w_{i1} = \frac{1000000 \times E_{ctm}(t) \times \varepsilon(t)^2}{\gamma \times f} \quad \text{(mm)}$$  \hspace{1cm} (5)

The change $\Delta w_n(t)$ and the development of the crack width $w_n(t)$ follows from:

$$\Delta w_n(t) = \frac{1000000 \times E_{ctm}(t) \times \varepsilon_n(t)^2}{\gamma \times f} \quad \text{(mm)}$$  \hspace{1cm} (6)

$$w_n(t) = w_{i1} + \Delta w_n(t) \quad \text{(mm)}$$  \hspace{1cm} (7)

The model considers in an indirect way the effect of the slab length in the cracks width development. However, the magnitude of the slabs length reduction in ShJS needs to apply a Correction Factor (CF) to the crack width under the joints of the traditional JPCP resulted of the modelling. AASHTO and MEPDG models relate directly the joint opening with the slab length, i.e. if the short slabs length of ShJS is 50% of the traditional slabs length, the crack width of the ShJS would be 50% of the value of the one in the traditional slab. The authors of the present paper have found in field measurements a reduction of crack width of 40% (i.e. CF=0.6), when the short slab length is 50% of the traditional slab length (Pradena and Houben, 2014a) that is the case modelled in this paper, in particular slab length of ShJS 2m, i.e. 50% of 4 m (traditional slab length). A CF 0.6 is equivalent to apply a safety factor of 1.2 to the calculations of the crack width made with the simplified expressions of AASHTO and MEPDG. The modelling takes into account shallow saw-cut associated to EESC (RJDs 20% and 25%) and saw-cut of RJD 30% in order to have a point of comparison.

The construction at the day or days when the temperature is highest in a location, i.e. the ‘warmest moment of the year’, produces the widest cracks under the joints (Houben, 2010a), so the most unfavourable conditions for the transfer of traffic loads at the joints. Hence, this is the construction time chosen for the modelling. The temperature is 35°C at the ‘warmest moment of the year’, the period of evaluation is 8640 hours, i.e. practically 1 year; the concrete grade C28/35 and friction 1.

### 3.3. Joint capacity to transfer traffic loads

The joint capacity to transfer traffic loads can be quantified by the Load Transfer Efficiency (LTE). In the present paper the LTE related with joint opening is obtained from the experimental verification of joint load transfer of the 3D finite-element analysis tool EverFE (Davids and Mahoney, 1999). The wider crack widths under the joints are used to the relation with the LTE, because they are the ones that control the JPCP design.
3.4. Joint deterioration

The evaluation of the effects of the JWS on the performance of JPCPs considers as a reference the joint seals behaviour and the fact that the costs associated to the joints seals needs to be justified by enhancing the performance of the JPCP. The evaluation takes into account JPCPs applications with different objectives (accessibility or mobility), time in-service (years and/or Equivalent Single Axle Loads, ESALs) and climatic conditions (rainfall and freeze-thaw action).

4. Results and evaluation

4.1. Joint activation

For RJD 20% and 25% the joint activation is 50%, hence the Effective Slab Length (EiSL) is not short anymore. Consequently, not only one set of truck wheels rest on a single slab and there is not a slab curling reduction. Because the EiSL is longer than the designed slab length of 2 m, the effective stresses produced for the traffic and the slab curling are higher in the JPCPs in-service than the ones considered originally in the design. This situation produces deterioration of the pavement and eventually cracks on the slabs. Moreover, where there are joints that remain uncracked, there is a waste of money and time, saw-cutting the joints, preparing the joints to receive the seal, installing the seal and dowels bars at uncracked joints.

For the RJD 30% the joint activation is 100%, hence the EiSL is 2 m, i.e. the slabs are working as they were designed.

4.2. Joint opening and capacity to transfer traffic loads

In undowelled JPCPs, a LTE 70% or higher is generally considered appropriate to a good performance. According to the experimental verification of the joint load transfer of the finite-element software EverFE, the crack width under the joints must be 1.2 mm as maximum for a LTE ≥ 70% (Davids and Mahoney, 1999). For the analysed conditions that is produced when the saw-cut is at least 30% RJD (Fig. 2a).

![Fig. 2.](image)

(a) Crack width – LTE for different RJD (a) and ShJS at a bus lane at Concepción City downtown in Chile (b).

At the University of Illinois, U.S.A. an Accelerated Pavement Testing (APT) of JPCPs with short slabs (without dowels bars) was performed. The APT has shown that the LTE converged to values over 70%. In fact, part of the conclusions of that study were: the smaller slab sizes maintained a medium to high LTE over the accelerated loading period for all slab thicknesses without the development of any JF. And the fatigue performance of short slabs, in terms of allowable number of ESALs, significantly exceeds the allowable traffic on the equivalent thickness of traditional JPCPs (Roesler et al, 2012). This good performance is observed in different projects in Chile as well. For instance the Fig.2b shows a JPCP with ShJS of a bus lane in the main avenue of Concepcion City downtown in Chile, where no JF was detected after 7 years in-service.

4.3. Joint deterioration

In U.S.A more than 100 sections with and without seals have been investigated in different climates, including zones with rainfall levels over 1500 mm/year and 8 states with freeze-thaw action. According to the comparative analysis of joints deterioration, the joints seals would not enhance pavement performance (Hall, 2009). But the most remarkable experience in U.S.A. is the one of the Wisconsin Department of Transportation (WisDOT) that has investigated for 50 years joint filling/sealing in urban and rural areas, for various traffic levels and truck loadings, type of bases, soils and joint spacings, with and without dowels bars. The results have always shown that sealing does not enhance pavement performance.
Even they have concluded that the pavements with unsealed joints performed better than the pavements with sealed joints and the pavements with shorter joint spacings performed better than the pavements with longer joint spacings (Shober, 1987). In 1995 only Wisconsin reported that it had dispensed with joint sealing entirely, reporting savings of 6,000,000 US dollars annually with no loss in pavement performance (Shober, 1997). In 2000, 3 states (Alaska, Hawaii and Wisconsin) reported they do not apply joint sealing (Jung et al, 2011). Hawaii is the wettest state of U.S.A. with an average annual rainfall of 1785 mm, and Alaska has oceanic climate in the occidental coast and continental and arctic climates in the rest of the state, hence rainfall and freeze-thaw effects in the joints.

Austria, Belgium and Spain have achieved a suitable service life for up to 30 years with JWS and undoweled JPCPs for country roads with light truck traffic (Burke and Bugler, 2002). Austria and Belgium are countries with, at least, rainfall over 500 mm/year in all the country, and big part of the territory with more than 1000 mm/year. Both countries include extensive regions with temperatures below zero as well (freeze-thaw). In Chile JPCPs with ShJS, synthetic fibers and JWS have been built for LVRs with less than 1.000.000 ESALs in areas with rainfall over 500 mm/year and 1000 mm/year respectively. Although there is not enough experience in Chile yet, the JWS in LVRs can be considered feasible due to the LVR objective (accessibility), the low speed, the experience of Austria, Belgium and Spain, and due to the smaller joint opening in JPCPs with ShJS, even more when fibers are included (Pradena and Houben, 2014b).

Measurements of JF and IRI were made on JPCPs with JWS in Guatemala after 3, 8, 15 and 22 million ESALs. The JF values were always less than 2 mm and the IRI values less than 2.4 m/km (Salgado, 2011). Guatemala is a mountainous country with level of rainfall over 1000 mm/year in almost the whole country, and zones with more than 1500 mm/year.

Chile has experience with JWS at different climatic conditions, time in-service and JPCPs applications. For instance, applications as bus corridors in areas with moderate rainfall (between 500 and 1000 mm/year) have shown good performance. Local streets with JWS have not shown joints affected by spalling, according to the classification of the FHWA (FHWA, 2003), after 2.5 years to 6 years in-service in areas with more than 1000 year/mm of rainfall and even potential freeze-thaw action (Pradena and Houben, 2014b). In addition, the successful cases of Guatemala can be assimilated to the ESALs of local streets and bus corridors. Even more, a possible extrapolation of JWS to more exigent cases can be suggested considering stricter specifications for saw-cuts (width ≤ 2.5 mm), base fines content (≤ 6%) and ShJS to obtain smaller joint openings. This suggestion is based specially in the levels of IRI similar to a new JPCP in the rural roads with JWS at Guatemala, the 50 years of excellent experience of WisDOT (even better than with sealed joints) and the fact that nowadays is possible to make saw-cuts of 3 mm or less, instead of the JWS 3-6 mm wide considered in the WisDOT experiences (Pradena and Houben, 2014b).

5. Conclusions

The innovations analysed contribute to a sustainable infrastructure as they can maintain, and even improve, the traditional life-cycle performance of CPs with lower initial costs. Nevertheless, for the design hypotheses to be valid, it is necessary to assure the joints activation and to limit the joints opening to 1.2 mm. With this purpose, for the analysed conditions, it is recommended to cut the joints at least at 30% of the JPCP thickness. JWS with thin blade (≤ 3 mm) and limited fines in the base (≤ 8% passing 75 µm) can be used in streets, LVRs, parking lots and any JPCP application where the seals are not working well enough. Even an extrapolation to more exigent cases could be possible with stricter specifications for saw-cuts (width ≤ 2.5 mm), base fines content (≤ 6%) and the use of JPCPs with short joint spacing to obtain smaller joint openings.

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