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Cost-effective joints configurations of concrete pavements for a sustainable infrastructure

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Abstract

Nowadays, there are Concrete Pavements (CPs) with Joints Configurations (JCs) that reduce initial costs about 20%. But are these JCs produced by Early-Entry Saw-Cutting (EESC), Unsealed Joints (UJs) and Shorter Joint Spacing (ShJS) able to maintain the traditional performance of CPs? The aim of this paper is to analyze the effects of the joints behaviour (JB) on the performance of CPs with these JCs. The JB is characterized by joints activation, opening, deterioration and Load Transfer Efficiency (LTE), not in an isolated but in a comprehensive way to determine not only the complete JB, but their effects on the CPs performance, so upon the users. The paper contributes not only with a comprehensive analysis of the innovative JCs, but also with new field experiences, that allow concluding the JCs can maintain or even improve the traditional performance of CPs if the saw-cutting depth ≥ 30% to assure 100% joints activation, joints opening ≤ 1.2 mm, so LTE ≥ 70%. UJs with thin blade (≤ 3 mm) and limited fines in the base can be used in CPs applications as streets, low volume roads, parking lots, bus corridors (moderate rainfall) and any CP where the seals do not work well.

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Introduction

The objective of this article is to analyze the effects of the Joints Behaviour (JB) on the performance of Concrete Pavements (CPs) with Joints Configurations (JCs) produced by Early-Entry Saw-Cutting (EESC), Unsealed Joints (UJs) and Shorter Joint Spacing (ShJS). In fact, nowadays there are JCs available that can reduce initial costs of CPs. That issue is important because even when CPs are a sustainable paving alternative, durable, that do not need periodic invasive maintenance interventions, they are hardly chosen when only initial costs, instead of life-cycle costs, are considered in the evaluation. This paper deals with the question if the innovative JCs are able to maintain the favourable traditional life-cycle performance of CPs.

EESC consists of a shallow cut (up to 30 mm depth) that allows cut the joints 3-5 hours after concrete placement (McGovern, 2002). Hence, EESC should be useful to avoid random cracking of slabs because it relieves internal concrete stresses created by the friction of the slab with the base that restricts the deformations produced by shrinkage and temperature changes in the concrete. It is postulated that the saw-cut can be shallower at early age, taking advantage of the changes in moisture and temperature at the slab to help initiate the crack below the saw-cut (Zollinger et al, 1994). However, a report of the Illinois Center for Transportation recommends, before a general adoption, a Phase II study to evaluate the long-term performance of Jointed Plain Concrete Pavements (JPCPs) with EESC, under more unfavourable conditions than Phase I study (Krstulovich et al, 2011). Moreover, in a research of the Louisiana Transportation Research Center, the joints created by EESC needed to be sawn deeper because the slow joint activation (Rasoulian et al, 2005).

The function of the joint seals is basically to prevent the pumping, the Joint Faulting (JF) and spalling. The costs of sealing transverse contraction joints it is estimated between 2 and 7% of the initial construction cost of a JPCP (Hall, 2009). And keeping the joints sealed for 10 years, cost 45% more than a JPCP with UJs (Shober, 1987). However joint seals are not working well enough, long-term JF data shows a strong correlation with annual rainfall (Jung et al, 2011). Therefore, there is increased interest in eliminating joint sealants. The UJs consist in a saw-cut as narrow as possible, to prevent spalling due to coarse material in the joint, and a base with limited fines to prevent pumping and JF. The UJs can be applied to JPCPs with traditional slabs or ShJS (Pradena and Houben, 2014a).

When the joint spacing is the order of 50% of the traditional JPCP less truck wheels rest on a single slab and the slab tensile stresses are reduced also because the 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 20% (Covarrubias, 2012). Certain aspects of this technology has been patented (Covarrubias, 2012). The pavement design features include, between others, granular base with limited fines (≤8% passing 75 μm); thin saw-cut at joints (2-3 mm thick); no joints sealing and no dowel bars (Roesler, 2013). Accordingly, the joint capacity to transfer traffic loads depends of the crack width under the joints (aggregate interlock). A low Load Transfer Efficiency (LTE), accelerate the JPCPs deterioration, affecting their performance.

In this article the JB is characterized by joints activation, opening, deterioration and LTE, not in an isolated but in a comprehensive way to determine not only the complete JB, but their effects on the JPCPs performance, so at the end upon the users. The paper contributes not only with a comprehensive analysis of the innovative JCs, but also with new field experiences. Furthermore, all studies of the literature review regarding to the evaluation of EESC referred to traditional JPCPs, but not to JPCPs with ShJS (Pradena and Houben, 2014b). All these studies allow concluding that the innovative joint configurations analyzed contribute to a sustainable infrastructure as they can maintain, and even improve, the traditional life-cycle performance of CPs if the design hypothesis are valid. With this purpose, for the analyzed conditions, it is recommended to cut the joints at least at 30% of the CPs thickness in order to assure 100% joints activation, joints opening ≤ 1.2 mm, so LTE ≥ 70%. UJs with thin blade (≤ 3 mm) and limited fines in the base (≤ 8% passing 75 μm) can be used in JPCPs applications as streets, low volume roads, parking lots, bus corridors (moderate rainfall) and any JPCP where the seals do not work 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 ShJS to obtain smaller joint openings.

The Section 1 of this paper presents the methods to evaluate the JB on the performance of JPCPs. It describes how the calculations of the joints activation and opening are made with a model developed by the authors. The section also states that the relation LTE-crack width (joint opening) is determined by the results of a finite-element analysis tool and that the analysis is completed with field data of the innovative JCs. Section 2 gives the results and evaluation of the joint activation, the relation joint opening-LTE, and the joint deterioration. Finally, Section 3 describes a discussion about the importance of the valuable information obtained from practical experiences even when they could not be part of formal studies.

1. Methods to evaluate the joint behaviour on the performance of JPCPs

The expectations of the costumer must be considered in the life-cycle 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 JB on the JPCP performance, so at the end upon the users and the costs. For instance, JF is the major contributor to the JPCPs 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 JB is characterized by the joint activation opening, deterioration and LTE, not in an isolated but in a comprehensive way to determine not only the complete JB, but their effects on the JPCPs performance. The paper contributes not only with this comprehensive analysis of the innovative JCs, but also with new field experiences.

1.1. Joint activation and opening

The calculations of the joints activation and opening are made with a model developed by the authors. The details of the model can be found in Houben (2010a, 2010b) and Pradena and Houben (2012), but the basic formulation is that the occurring tensile stresses in a JPCP is product of the restricted deformation follow from Hooke's law, but affected by the viscoelastic behaviour of the concrete (relaxation) (Houben, 2010a).

$$\sigma(t) = g * R * E(t) * \varepsilon(t) \qquad \text{(MPa)} \qquad (1)$$

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

$$g = h/(h - jd) \qquad \text{(-)} \qquad (2)$$

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

The model was developed originally for JPCPs with traditional slabs length (Houben, 2010b) and it requires a Correction Factor (CF) for the magnitude of the slab reduction of ShJS, in order to 50% of traditional JPCPs. The authors have found in field 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, 2014c) that is the case modelled in this paper, in particular slab length of ShJS 2m, i.e. 50% of 4 m (traditional slab length). AASHTO and MEPDG use simplified models that relate directly the joint opening with the slab length (AASHTO, 1993; NCHRP, 2004); hence a CF 0.6 is equivalent to apply a safety factor of 1.2 to the simplified expressions of AASHTO and MEPDG. The modelling takes into account shallow saw-cut associated to EESC (Relative Joint Depth, RJD, 20% and 25%) and the traditional saw-cut of RJD 30% and 35%. 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 LTE. 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.

1.2. Joint capacity to transfer traffic loads

The relation joint opening-LTE is determined using 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. In addition, the LTE results of the Accelerated Pavement Testing (APT) over JPCP with ShJS at the University of Illinois, USA are considered (Roesler et al, 2012). The performance of these tests sections and the experiences of Chilean ShJS JPCPs without dowels bars are considered in the evaluation. All of them correspond to concrete slabs over granular base that are the most critical conditions for LTE.

1.3. Joint deterioration

The evaluation of the effects of the UJs 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) (Pradena and Houben, 2014d). The UJs can be applied to JPCPs with traditional slabs or ShJS.

2. Results and evaluation

2.1. Joint activation

In traditional JPCPs, for all the RJDs analyzed the joints activation is 100%. But in JPCPs with ShJS, the joint activation is 50% for RJD 20% and 25%, hence the Effective Slab Length (EfSL) is longer than the designed slab length of 2 m. Then the effective stresses produced for the traffic and the slab curling are higher than the ones considered in the design. Moreover, there is a waste of money and time saw-cutting the uncracked joints. For the RJD 30% and 35% the joint activation is 100%, hence the EfSL is 2 m, i.e. the slabs are working as they were designed. Two projects of JPCPs with ShJS constructed in similar conditions to the modelled ones were visited in Chile. The first one, with RJD 20%, presented 60% of joint activation, very close to the 50% resulting from the model. A visual inspection was made over the second ShJS JPCP as well. This second project, with RJD 30%, presented 100% of joint activation. In these two projects no random cracking was produced. Furthermore, as part of the present study, several traditional and short slabs JPCPs under construction were visited in Chile, with only EESC or in combination with the conventional method (to reach larger RJD). In all cases, was verified the effectiveness of the EESC to avoid random cracking.

2.2. 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 this and the results show in Figure 1 left, dowels bars should be applied in traditional JPCPs for a better LTE. However, acccording to Hansen and Jensen (2001) a crack width 2.1 mm (RJD 30% and 35% in Figure 1 left) still could provide adequate LTE when strong coarse aggregate are used (this situation requires further investigation). In JPCPs with ShJS, the crack width under the joints must be 1.2 mm as maximum for a LTE ≥ 70%. For the analyzed conditions that is produced when the saw-cut is at least 30% RJD (Figure 1 rigth).

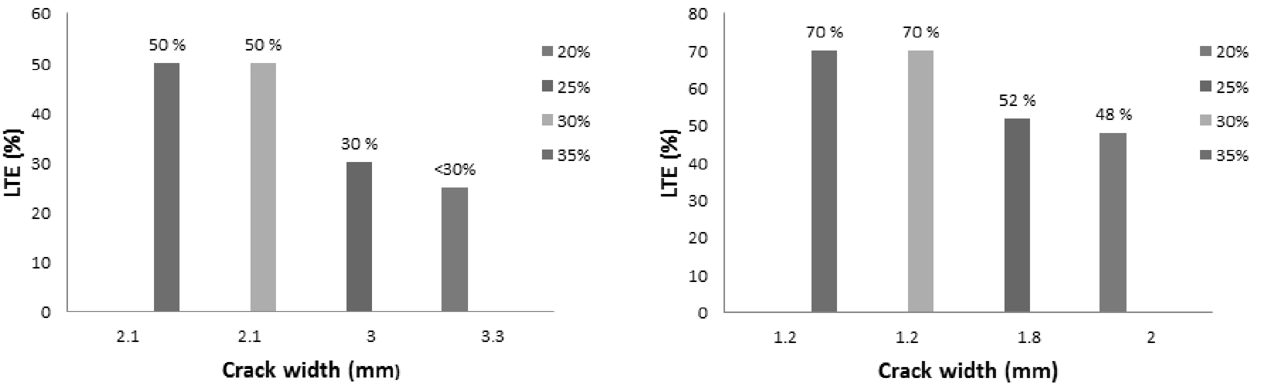

Figure 1 – Crack width – LTE for different RJD in traditional JPCPs (left) and JPCPs with ShJS (rigth). Source: authors.

The APT over short slabs 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 (Roesler et al, 2012). This good performance is observed in different projects in Chile as well. For instance, in the main avenue of Concepción City, a JPCP with ShJS of a bus lane do not present slabs cracking or JF after 7 years in-service (Pradena and Houben, 2014a) and Salsilli et al (2013) reports the remarkable performance of a test section of JPCP with ShJS in the main avenue of Santiago City after 13.000.000 ESALs.

2.3. Joint deterioration

In USA more than 100 sections with and without seals were investigated in different climates, including zones with rainfall levels over 1500 mm/year and 8 states with freeze-thaw action. The conclusion was, the joints seals would not enhance pavement performance (Hall, 2009). But the most remarkable experience in USA 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 JPCPs with unsealed joints performed better than the ones with sealed joints, and the JPCPs with shorter joint spacings performed better than the ones with longer joint spacings (Shober, 1987). In 1995 only Wisconsin reported that it had dispensed with joint sealing entirely, saving 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 (1785 mm/year), and Alaska has oceanic, continental and artic climates, hence rainfall and freeze-thaw effects in the joints (Pradena and Houben, 2014d).

Austria, Belgium and Spain have achieved a suitable service life for up to 30 years with UJs and undoweled JPCPs for country roads with light truck traffic (Burke and Bugler, 2002). Austria and Belgium are countries with rainfall of at least 500 mm/year, and big part of the country over 1000 mm/year. Both countries include extensive regions with temperatures below zero as well (freeze-thaw). In Chile JPCPs with ShJS and UJs 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 UJs in LVRs can be considered feasible due to the LVR objective (accessibility), their low speed, the experience of Austria, Belgium and Spain, and due to the smaller joint opening in JPCPs with ShJS (Pradena and Houben, 2014c).

Measurements of JF and IRI were made on JPCPs with UJs in Guatemala after 1, 3, 8 and 22 million ESALs. The JF values were always less than 2 mm and the IRI less than 2.4 m/km (Covarrubias, 2012). 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 UJs 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 after 7 years (Pradena and Houben, 2014d). WisDOT UJs are 3 - 6 mm wide, they become filled with fine incompressible material that does not produce spalling (Shober, 1997). This behaviour has been observed in local streets in Chile as well (Figures 2 and 3). Chilean streets have not shown joints affected by spalling, according to the classification of the Federal Highway Administration, USA (Miller and Bellinger, 2003), after 2.5 to 6.5 years in-service in areas with more than 1000 year/mm of rainfall and even potential freeze-thaw action (Pradena and Houben, 2014d). Figures 2 and 3 show examples of the good behaviour of the UJs in Chile.

Figure 2 – Traffic demand and UJs state in a local street after 2.5 years (saw-cut 3 mm). Source: Authors.

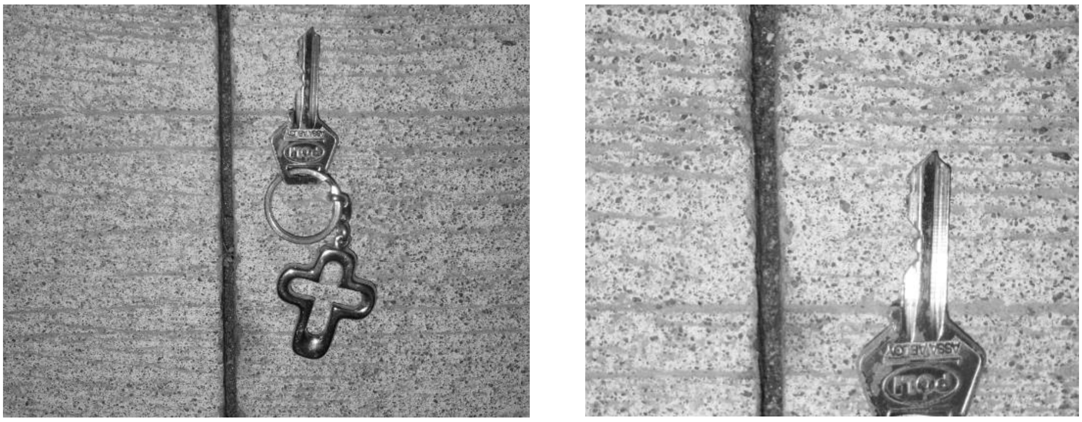

Figure 3 – UJs state of a residential steet after 6.5 years (saw-cut 4 mm). Source: Authors.

In addition, the successful cases of Guatemala can be assimilated to the ESALs of local streets, bus corridors and rural roads. Even more, a possible extrapolation of UJs 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 in the levels of IRI similar to news JPCPs in Guatemala, the 50 years of 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 UJs 3-6 mm wide considered in the WisDOT experiences (Pradena and Houben, 2014a).

3. Discussion

Even when practical experiences could not be part of formal studies, they can give valuable information. In fact, the innovation EESC was introduced by a concrete pavement contractor. In the case of one of the JPCPs with ShJS visited in Chile, the contractor made a practical modification in the EESC equipment in order to reach a RJD at least of 35% producing 100% joint activation. Moreover, it was possible to check in the field another contractor's opinion that it would be less difficult to make deeper saw-cuts with conventional equipment but using a thin blade (2 mm), as is the case for JPCPs with UJs. Finally, a simple visual inspection of different JPCPs under construction was useful to evaluate the effectiveness of EESC in eliminating the random cracking.

Conclusion

This article deals with the question if the innovative JCs produced by EESC, UJs and ShJS are able to maintain the traditional performance of JPCPs. Accordingly, the aim of the paper is to analyze the effects of the JB on the performance of the JPCPs with EESC, UJs and ShJS. For that the JB is characterized by joints activation, opening, deterioration and LTE, not in an isolated but in a comprehensive way to determine not only the complete JB, but their effects on the JPCPs performance, so at the end upon the users. The paper contributes not only with a comprehensive analysis of the JCs, but also with new field experiences. Furthermore, all studies of the literature review regarding to the evaluation of EESC referred to traditional JPCPs, but not to JPCPs with ShJS. All these allow concluding that the innovative JCs contribute to a sustainable infrastructure as they can maintain, and even improve, the traditional life-cycle performance of CPs if the design hypotheses are valid. With this purpose, for the analyzed conditions, it is recommended to cut the joints at least at 30% of the JPCPs thickness in order to assure 100% joints activation, joints opening ≤ 1.2 mm, so LTE ≥ 70%. UJs with thin blade (≤ 3 mm) and limited fines in the base (≤ 8% passing 75 μm) can be used in JPCPs applications as streets, low volume roads, parking lots, bus corridors (moderate rainfall) and any JPCP where the seals do not work 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 ShJS to obtain smaller joint openings.

As the paper deals with the performance of innovations in JPCPs the empirical support is limited, being recommended in future research extends the field observations over the complete life-cycle of these innovations. For instance, in the case of UJs, the ideal situation is to compare duplicate sealed and unsealed JPCPs in the life-cycle. In the present paper, conclusions have been obtained directly from the experiences presented, and indirectly from the assimilations of ESALs. Finally, as it was mentioned, the effects of strong coarse aggregate over the LTE require further investigation.

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References

AASHTO (1993). AASHTO guide for design of pavement structures.

Burke M. P., & Bugler J. W. (2002). The Long-Term Performance of Unsealed Jointed Concrete Pavements. 81st Transportation Research Board Annual Meeting, Washington D.C., USA.

Covarrubias, J. P. (2012) Design of concrete pavement with optimized slab geometry. Revista Ingeniería de Construcción, 27 (3), 181 – 197.

Davids, W. G., & Mahoney, J. P. (1999). Experimental Verification of Rigid Pavement Joint Load Transfer Modeling with EverFE. Transportation Research Record 1684, 81-89.

Hall, K. A. (2009) Performance of Sealed and Unsealed Concrete Pavement Joints (TechBrief FHWA-HIF-09-013).

Hansen ,W., & Jensen, E. A. (2001). Transverse Crack Propagation of JPCP as Related to PCC Toughness (Report RC-1404).

Houben, L. J. M. (2010). Model for Transversal Cracking in Non-Jointed Plain Concrete Pavements as a Function of the Temperature Variations and the Time of Construction. Proceedings of the 7th International DUT-Workshop on Design and Performance of Sustainable and Durable Concrete Pavement, Sevilla, Spain.

Houben, L. J. M. (2010). Transversal Cracking in Jointed Plain Concrete Pavements for Dutch Climatic Conditions. Proceedings of the 7th International DUT-Workshop on Design and Performance of Sustainable and Durable Concrete Pavement, Sevilla, Spain.

Jung, Y. S., Neshvadian, K., & Zollinger, D. (2011) Seal No Seal. Workshop of Seal No Seal Program, Utah, USA.

Krstulovich, J. M., Van Dam, T. J., & Smith, K. D. (2011). Evaluation of the long term durability of rigid pavement joints cut using early-entry saws (Series No. 11-076).

McGovern, M. (2002). The Latest on Early-Entry Sawing. Concrete Technology Today, 23(3).

Miller, J. S., & Bellinger, W. Y. (2003). Distress Identification Manual for the Long-Term Pavement Performance Program. (Report No. FHWA-RD-03-031).

NCHRP (2004). Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Part 3–Design Analysis. Transportation Research Board.

Pradena, M. A. & Echaveguren, T. B. (2008). Quality Management in Road Maintenance Based on the Approach to the Client Principle (in Spanish). Revista de la Construcción, 7(2), 102-108.

Pradena, M. A. & Houben, L. J. M. (2012). Early age deformation and internal stresses in jointed plain concrete pavements for Dutch conditions. Proceedings of the 2nd International Conference on Microstructural-related Durability of Cementitious Composites, Amsterdam, the Netherlands.

Pradena, M. A. & Houben, L. J. M. (2014). Innovations in Concrete Pavements for a Sustainable Infrastructure. Proceedings of the 2nd International Conference on Traffic and Transport Engineering, Belgrade, Serbia.

Pradena, M. A., & Houben, L. J. M. (2014). Sustainable Pavements: Influence of the Saw-Cutting Method on the Performance of JPCP. Proceedings of the 14th International Multidisciplinary Scientific GeoConference, Varna, Bulgaria.

Pradena, M. A., & Houben, L. J. M. (2014). Sustainable Pavements: An Analysis of the Crack Width in Jointed Plain Concrete Pavements with Short Slabs. Proceedings of the 14th International Multidisciplinary Scientific GeoConference, Varna, Bulgaria.

Pradena, M. A., & Houben, L. J. M. (2014). Sustainable Pavements: Unsealed Joints in Jointed Plain Concrete Pavements, Proceedings of the 14th International Multidisciplinary Scientific GeoConference, Varna, Bulgaria.

Rasoulian, M., Titi, T., & Martinez, M. (2005). Evaluation of Narrow Transverse Contraction Joints in Jointed Plain Concrete Pavements. Proceedings of the 8th International Conference on Concrete Pavements, San Francisco, USA.

Roesler, J. R., Cervantes, V. G., & Amirkhanian, A. N. (2012). Accelerated Performance Testing of Concrete Pavement with Short Slabs. International Journal of Pavement Engineering, 13(6), 494-507.

Roesler, J. R. (2013). Thinner Concrete Pavement Technologies. Meetings of the National Concrete Pavement Technology Center Philadelphia, USA.

Salsilli, R., Wahr, C., Delgadillo, R., Huerta, J., & Sepúlveda, P. (2013). Design Method for Concrete Pavements with Short Slabs Based on Westergaard's Equations and Dimensional Analysis.. 92nd Transportation Research Board Annual Meeting, Washington D.C., USA

Shober, S. F. (1987). Are pavement joint sealants always necessary? (Publication #C870289).

Shober, S. F. (1997). The Great Unsealing: A Perspective on PCC Joint Sealing. Transportation Research Record 1597, 22-33.

Zollinger, D. G., Tang, T., & Xin, D. (1994) Sawcut Depth Considerations for Jointed Concrete Pavement Based on Fracture Mechanics Analysis. Transportation Research Record 1449, 91-100.