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Pradena, Mauricio; Houben, Lambert

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Joint faulting behaviour of innovative short concrete slabs

Author 1

- Mauricio Pradena, MSc, PhD
- Assist. Prof. Department of Civil Engineering, University of Concepcion, Concepcion, Chile

Author 2

- Lambert Houben, MSc
- Assoc. Prof. Section Pavement Engineering, Delft University of Technology, Delft, the Netherlands

Full contact details of corresponding author.

Mauricio Pradena,

Department of Civil Engineering

University of Concepcion

Edmundo Larenas 215, Barrio Universitario

Concepción, Chile

Phone: +56(41)2203576

E-mail: mpradena@udec.cl

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Abstract

Pavements are one of the largest assets of a city and their functional condition (ride quality) is priority for their clients. In Jointed Plain Concrete Pavements (JPCPs) the presence of Joint Faulting (JF) reduces the ride quality. But nowadays, short slabs are available as a cost-effective JPCP innovation. The objective of this article is to analyse the joint faulting behaviour of JPCPs with short slabs. For that, a deterioration model to predict it and trends of JF observed in short slabs of Chile and USA are considered. The HDM-4 model always yields lower JF per joint in short slabs than in traditional ones. But real-world short slabs are showing not only lower JF per joint (that the modelled JF) but also that more joints not necessarily means more JF per length of pavement that affect the ride quality. One of the relevant explanatory factors for it is the radical reduction of crack width at joints, which produces a fundamental increase of the Load Transfer Efficiency. To maintain the favourable behaviour observed in the field it is recommended to assure the joint activation and to provide adequate stiffness of the layers below the short slabs.

Keywords

Infrastructure; Roads & highways; Municipal & Public Service Engineering; Pavement Design

List of notation

<i>JPCP</i>	is the jointed plain concrete pavement
<i>JF</i>	is the joint faulting
<i>LTE</i>	is the load transfer efficiency
<i>HDM-4</i>	is the Highway Development and Management system, version 4
<i>AASHTO</i>	is the American Association of State Highway and Transportation Officials
<i>ESALs</i>	is the cumulative equivalent single axle loads

1. Introduction

Pavements are one of the largest assets of a city (Whiteley-Lagace *et al.*, 2011). In particular, Jointed Plain Concrete Pavements (JPCPs) are considered a sustainable alternative that can resist high traffic demands and do not need regular invasive interventions of maintenance that affect the users. Because of these characteristics, JPCPs are especially attractive in critical traffic hubs as intersections or roundabouts, pavements with predominant high traffic demands (urban avenues for instance) or bus corridors. JPCPs are also convenient for bus stops and bus stations as they can resist without deformations low speeds traffic loads and they are resistant to aggressive agents as oils, greases and fuels. Finally, the brightness of the concrete helps to counteract urban warm-up effects, improve visibility and reduce lightening costs.

According to the principle of continual improvement new possibilities of JPCPs have been developed. For instance, new technologies associated to the construction and performance of the joints of JPCPs. This has allowed to experiment with reductions of joint spacing despite the traditional practice to avoid more joints because of the potential distresses and costs of construction and maintenance. But short concrete slabs can reduce the thickness of the concrete because of the traffic load configuration and the curling reduction (Roesler *et al.*, 2012; Covarrubias, 2011). Even more, the construction costs can be reduced up to 25% due to the use of joints without seals and without dowels bars (Covarrubias, 2011). Considering this and the traditional performance of JPCPs, short slabs could be a potential alternative for sustainable pavements. Other design features of shorts slabs JPCPs are: slab length < 2.5 m, unsealed joints produced by thin saw-cuts (2-3 mm thick), granular base with limited fines ($\leq 6\%$ to 8% passing $75 \mu\text{m}$) (Covarrubias, 2011; Salsilli *et al.*, 2015). Roesler *et al.* (2012), Covarrubias (2011) and Salsilli *et al.* (2015) have developed valuable studies of the excellent structural behaviour of the JPCPs with short slabs. Actually, Roesler *et al.* (2012) has shown that the fatigue performance of short jointed slabs in terms of allowable number of ESALs significantly exceeds the allowable traffic on the equivalent thickness of conventional JPCPs.

However, an integral analysis must include explicitly the needs of the clients for pavements. In effect, the satisfaction of the clients is a goal that any service or product provider should strive for Haas and Hudson (1996). Road users and transportation agencies are the largest groups of clients for pavements. Both assign priority to the functional pavement condition, in particular to the ride quality (Haas and Hudson, 1996). And the major single contributor to a reduced ride quality in JPCPs is the joint faulting (Bustos *et al.*, 1998; Jung *et al.*, 2011) which is the elevation difference between the edges of a transverse joint (Morosiuk *et al.*, 2004). Hence, the objective of the present paper is to analyse the joint faulting of innovative jointed plain concrete pavements with short slabs. For that, a deterioration model to predict

the joint faulting is applied and trends of joint faulting observed at short slabs JPCPs in USA and Chile are also considered in the evaluation.

2. Method to evaluate the joint faulting

2.1. Modelling the joint faulting

A new design configuration needs to be compared with the traditional one in order to evaluate if effectively it represents an improvement in the design that affects positively the field performance (Montgomery, 2012). As the deterioration models to predict the Joint Faulting (JF) were developed originally for traditional JPCPs (Wu et al., 1993; Simpson et al., 1994; ERES, 1995; Owusu-Antwi et al., 1997; Yu et al., 1998; Titus-Glover et al., 1999; Hoerner et al., 2000) it is necessary to take into account some considerations for the modelling and evaluation of the JF in short slabs. In this way, the useful model for this purpose needs to fulfil the following requirements:

- Have a mechanistic component, i.e. to incorporate relevant variables that influence the development of joint faulting.
- Directly incorporate (and be sensitive to) variables that allow the comparison between traditional and short slabs JPCPs
- Allow the evaluation of non-dowelled JPCPs
- Has demonstrated suitable predictions of joint faulting at traditional JPCPs (especially at the locations of the short slabs projects)
- The variables required need to be available in projects of short slabs with joint faulting information

The fulfilment of these requirements provides a well-established base to model and evaluate the joint faulting in the new developed JPCPs with shorts slabs. In this way the model of ERES (1995) for non-dowelled JPCPs is chosen because not only it includes directly the slab length itself but also others relevant variables that influence the development of joint faulting, such as rainfall, characteristics of the base and traffic loads. In addition, the model of ERES (1995) has been included in the Highway Development and Management system HDM-4 which has been widely used around the world for the prediction of pavement deterioration.

As shorts slabs are a recent development, the number of projects with information of the joint faulting is limited. Then the availability of the variables required by the model is important. A Chilean company has patented certain aspects of the technology of short slabs (Covarrubias, 2011). The majority of these projects are located in Chile and they have available information of the joint faulting and the variables required by the model of ERES (1995) represented by the Equation 1. In addition, the models of HDM-4 have been calibrated for different conditions, in particular for traditional non-dowelled JPCPs at Chilean conditions (Límite Ingeniería, 2009).

This contributes to a well-established base to the modelling of the joint faulting in short slabs (i.e. non-dowelled JPCPs) especially for the Chilean projects.

$$FaultND = f(ESALs, -\frac{h}{L}, -Cd, -Base, FI, MMP, -Days32, -Widened) \quad (\text{mm})$$

1.

In the Equation 1 *FaultND* is the mean transverse non-dowelled joint faulting (mm) ; *ESALs* is the cumulative equivalent single axle loads (millions/lane); *h* is the slab thickness (mm) ; *L* is the slab length (m); *Cd* is the drainage coefficient of AASHTO; *Base* is 1 if there is stabilized base, otherwise 0 ; *FI* = mean freezing index (°C-days); *MMP* is the mean annual precipitation (mm); *Days32* are the days with maximum temperature greater than 32°C, and *Widened* is 1 if there is a widened traffic lane, otherwise 0.

Roesler *et al.* (2012) made a structural comparison between short slabs and traditional JPCPs using the same thickness for both alternatives. The same principle is applied for the functional comparison. In effect, from the analysis of the Equation 1 is possible to observe that *ceteris paribus*, with the exception of the slab length, the traditional JPCP should bring higher values of joint faulting than the new design configuration with short slabs. This is show in Figure 1 using *h* = 200 mm; *Cd* = 1.15; *Base* = 0 (not stabilized); *FI* = 55 °C-days; *MMP*= 27 mm; *Days32* = 45; *Widened* = 0; *L* short slabs = 1.2 m; *L* traditional = 3.5 m.

2.2. Trends of joint faulting in short slabs projects

As shorts slabs are a recent development, the number of projects with information available of joint faulting is limited. The projects included in the joint faulting analysis of the present article are short slabs of Santiago city, in Chile (Salsilli *et al.*, 2015), an Accelerated Pavement Testing (APT) in Illinois, USA (Roesler *et al.*, 2012) and a bus lane at Concepcion city in Chile (Figure 2). These projects represent different climatic conditions, they have different geometric configurations and traffic demands. In addition all these short slabs are built over granular base which is the most unfavourable one for the production of joint faulting.

Even when a comprehensive process of calibration at short slabs (modification or creation of a new model) requires an improvement of the information of joint faulting of this new development, nowadays some interesting results and conclusions can be obtained from the clear trends that shorts slabs are showing

3. Results and analysis

The data used in the modelling of the Figure 1 correspond to one of the sections of the bus lane of Santiago city in Chile. And when the calibration factor of 0.51 for Chilean conditions is applied (Límite Ingeniería, 2009), the model yields an average joint faulting 1.0 mm after 12,500,000

ESALs (Table 1). However, in the field no joint faulting was detected (Salsilli *et al.*, 2015). The Table 1 presents the model results and the joint faulting observed in the real-world short slabs based on Roesler *et al.*(2012), Pradena and Houben (2015) and Salsilli *et al.* (2015).

As an example, the Figure 3 shows the effect of the slab thickness in the calculated joint faulting using the different slab thicknesses of the bus lane at Santiago city. According to the model, the thinner the slab the higher the joint faulting. However, in the field no measurable joint faulting was detected in any of the sections with different slab thickness (Salsilli *et al.*, 2015).

The model of ERES is sensitive to the changes of slab thicknesses (Figure 3), but it is not able to model correctly the effects of the slab length reduction of short slabs. The model of ERES was developed for predicting the JF of traditional JPCPs where the magnitude of the slab length reductions does not produce a radical difference in the Load Transfer Efficiency (LTE) as in short slabs JPCPs. In effect, short slabs JPCP with reduction of 50% of the slab length (with respect to the traditional JPCP) yields a reduction of 50% of the crack width under the joints (Pradena and Houben, 2016a) which produces a radical difference in the LTE by aggregate interlock, being the LTE fundamental in the production of JF (Ioannides *et al.*, 1990; SHRP 2, 2011; NCHRP, 2012).

In addition to the lower average joint faulting per joint, the projects are showing that more joints not necessarily means more accumulated joint faulting per length of pavement. In effect, even when the short slabs of the Table 1 have 2, 3 or even 4 times more joints than traditional JPCPs no measurable joint faulting was detected in the field. Then more joints not necessarily mean more accumulated JF per km that can increase the JPCP roughness. Furthermore, short slabs JPCPs in Guatemala show a maximum increase from the initial condition of only 0.25 m/km IRI after 22,000,0000 ESALs (Covarrubias, 2011). This excellent behaviour can be explained by the drastic reduction of 50% of the crack width at joints of short slabs, which produces a radical change of the LTE (Figure 4). Hence, despite the traditional practice to avoid more joints because of the potential distresses, the short slabs projects are showing that more joints not necessarily means more accumulated joint faulting per length of pavement that can affect the ride quality and the satisfaction of the clients for pavements.

At the same avenue with the short slabs at Santiago of Chile, hence with similar kind of traffic (Figure 5), a thin concrete overlay of a bus lane does not present signs of joint faulting after more than 7 years in-service. This thin concrete overlay of 100 mm thickness has square slabs of 0.6*0.6 m. Hence, under a correct design and construction process, more joints (even more than short slabs) does not necessarily mean more accumulated joint faulting per length of pavement.

In the case of the short slabs of thin concrete overlays the stiffness of the underlying old pavement contributes to the integral behaviour of the concrete overlay allowing the reduction of the concrete thickness. As JPCPs with short slabs can be thinner than the traditional ones, higher deflections can be expected (Roesler *et al.*, 2012). Similar to the case of thin concrete overlays it is important to provide adequate stiffness of the layers below the short concrete slabs that contribute to the integral behaviour of these pavements. In effect, the JPCPs with short slabs presented in this article have good support under the short concrete slabs. For instance, in the bus lane of Santiago city the California Bearing Ratio (CBR) of the granular base is 85%. Similar is the case in Temuco and Puerto Montt (Chile), with CBR 90% and 88% respectively. In the case of the Guatemala short slabs some of the sections were built over the old deteriorated asphalt pavement and others over a granular base with an equivalent modulus of subgrade reaction (k) of 110 MPa/m (Covarrubias, 2011).

The amount of rainfall can affect the development of joint faulting as well. Hence, precautions need to be taken especially in JPCPs situated in areas with high rainfall. For instance, a nonwoven geotextile prevents mixing of the subgrade and aggregate base layer, and adequate lateral drainage prevents lowering the support stiffness and unbound material shear strength (Roesler *et al.*, 2012).

4. Recommendation

Taking into account the clear trends of joint faulting shown by the short slabs, it is recommended to modify the model of ERES (1995) or to develop a new model able to represent better the joint faulting of this new development. For this, a dedicated study is necessary including comprehensive field measurements of joint faulting at short concrete slabs in different conditions and considering the LTE in the model. In effect, the LTE is fundamental in the production of joint faulting (Ioannides *et al.*, 1990; SHRP 2, 2011; NCHRP, 2012) and specifically in the case of non-dowelled JPCPs the prevention of joint faulting relies on effective load transfer through aggregate interlock (Ioannides *et al.*, 1990). In this way the reduction of 50% of the crack width under the joints of short slabs (Pradena and Houben, 2014) contribute decisively to the low joint faulting of this innovation. Then, despite the traditional practice to avoid more joints at the JPCPs, the reduction of joint spacing not only produces structural benefits (Roesler *et al.*, 2012; Covarrubias, 2011; Salsilli *et al.*, 2015) but also functional ones that not necessarily can be reflected by models of joint faulting developed for traditional JPCPs. For instance, the relevance that the model of ERES gives to the changes in slab thickness respect to the reduction of slab length of short slabs is inadequate. Therefore, a model to predict the joint faulting of short slabs must include the load transfer between slabs. As, in non-dowelled JPCPs, the LTE depends basically on the aggregate interlock, the LTE can be related with the crack width under the joints.

The final objective of the model is to serve to the necessities of the pavement clients. As mentioned, road users and transportation agencies assign priority to the ride quality of the pavement. In addition, the transportation agencies assign priority to the life-cycle cost effectiveness as well (Haas and Hudson, 1996). Then the model needs to predict adequately the joint faulting at short slabs and at the same time it needs to be practical and useful to the transportation agency. It includes the variables required by the modelling and the calibration process to evaluate short slabs at different conditions.

5. Practical relevance and potential applications

JPCPs are considered a sustainable alternative especially attractive in critical traffic hubs as intersections or roundabouts, pavements with predominant high traffic demands (as urban avenues for instance) or bus corridors. JPCPs are also convenient for bus stops and bus stations. As an innovation of JPCPs short slabs can be applied in the mentioned urban cases as well, especially considering the adequate JF behaviour presented in this article and the reduction of construction costs up to 25% (Covarrubias, 2011). Besides the adequate JF behaviour of short slabs JPCPs, more information about the general adequate performance of this innovation can be found for instance in Roesler *et al.* (2012), Pradena and Houben (2017) and Pradena and Diaz (2017).

6. Conclusions

The HDM-4 model always yields lower JF per joint in short slabs than in traditional ones. But real-world short slabs are showing not only lower JF per joint (that the modelled JF) but also that more joints not necessarily means more JF per length of pavement that affect the ride quality. Considering this and the priority that pavements clients assign to the ride quality, short slabs are an interesting sustainable pavement alternative. One of the relevant explanatory factors for this behaviour is the drastic reduction of crack width at joints of short slabs which produces a radical change in the LTE. In effect, short slabs can provide $LTE \geq 70\%$ even without dowels bars. To keep the trends observed in the field it is recommended to assure the joint activation (for a $LTE \geq 70\%$), to limit the fines of the base ($\leq 8\%$ passing $75 \mu\text{m}$), a narrow saw-cutting ($\leq 3 \text{ mm}$) and to provide adequate stiffness of the layers below the short slabs.

Finally and taking into account the clear trends of joint faulting shown by the short slabs, it is recommended to modify the model used in this paper or to develop a new model able to represent better the joint faulting of this new development. As the reduction of 50% of the crack width under the joints of the short slabs results fundamental in the low joint faulting of this non-dowelled JPCP, the model must include the load transfer trough aggregate interlock. As the final objective of the model is to serve the necessities of the pavement clients, it not only needs to predict adequately the joint faulting but also must be practical and useful to the transportation agency. It includes the variables required by the modelling and the calibration process to evaluate short concrete slabs at different conditions.

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Figures and table captions.

Figure 1. Development of average joint faulting in traditional and short slabs JPCPs

Figure 2. JPCP with short slabs at a bus lane in Concepción city, Chile (Reproduced from Pradena and Houben, 2015 by kind permission of STEF92 Technology)

Table 1. Characteristics of the test sections, traffic demands and joint faulting

Figure 3. Modelling results of joint faulting for different concrete thicknesses of short slabs

Figure 4. Relation LTE-crack width for traditional and short slabs JPCPs (Reproduced from Pradena and Houben, 2016b by kind permission of STEF92 Technology)

Figure 5. Concrete overlay at a bus lane of Santiago city, Chile (Reproduced from Pradena and Houben, 2015 by kind permission of STEF92 Technology)

Figures and table captions.

Figure 1. Development of average joint faulting in traditional and short slabs JPCPs

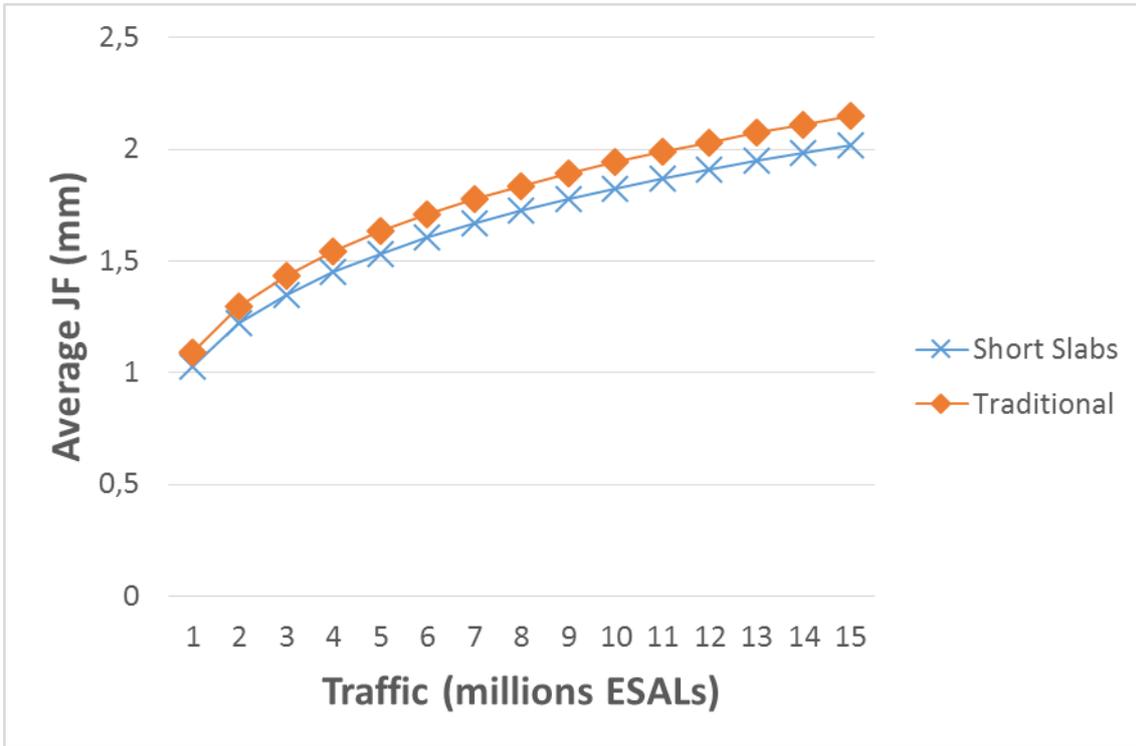


Figure 2. JPCP with short slabs at a bus lane in Concepción city, Chile (Reproduced from Pradena and Houben, 2015 by kind permission of STEF92 Technology)



Table 1. Characteristics of the test sections, traffic demands and joint faulting

Table 1. Characteristics of the test sections, traffic demands and joint faulting

City	Latitude	Climate	Slab length (m)	Slab thickness (mm)	Traffic (millions ESALs)	Calculated JF (mm)	Real-world JF (mm)	
Santiago	33°27' S	Mediterranean dry-summer	1.20	130	14.0	1.2	0	
				140	14.0	1.2		
				150	12.5	1.1		
				170	14.0	1.1		
				200	12.5	1.0		
Concepcion	36°49' S	Maritime tempered with mediterranean influence	2.00	200 ¹	1.5 ²	1.0	0	
Temuco	38°45' S	Oceanic with mediterranean influence	1.75	0.88	80	0.35	0.7	0
				1.17	80		0.7	
				80	0.8			
				100	0.7			
				120	0.7			
Puerto Montt	41°30' S	Oceanic with abundant rainfall	1.75	80	0.20	0.7	0	
				100		0.6		
				120		0.6		
Illinois (USA)	39°83' N	Humid continental	1.80	150	23.0	4.4	0	
					17.0	4.0		
					20.0	4.0		
				200	51.0	5.0		

(1) Estimated from the Chilean structural design guidelines (Ministry of Housing and Urbanism, 2016)

(2) Estimated on basis of the frequency of buses and the in-service time (7 years).

(*) For the Chilean sections the calibration factor 0.51 was applied (Límite Ingeniería, 2009)

Figure 3. Modelling results of joint faulting for different concrete thicknesses of short slabs

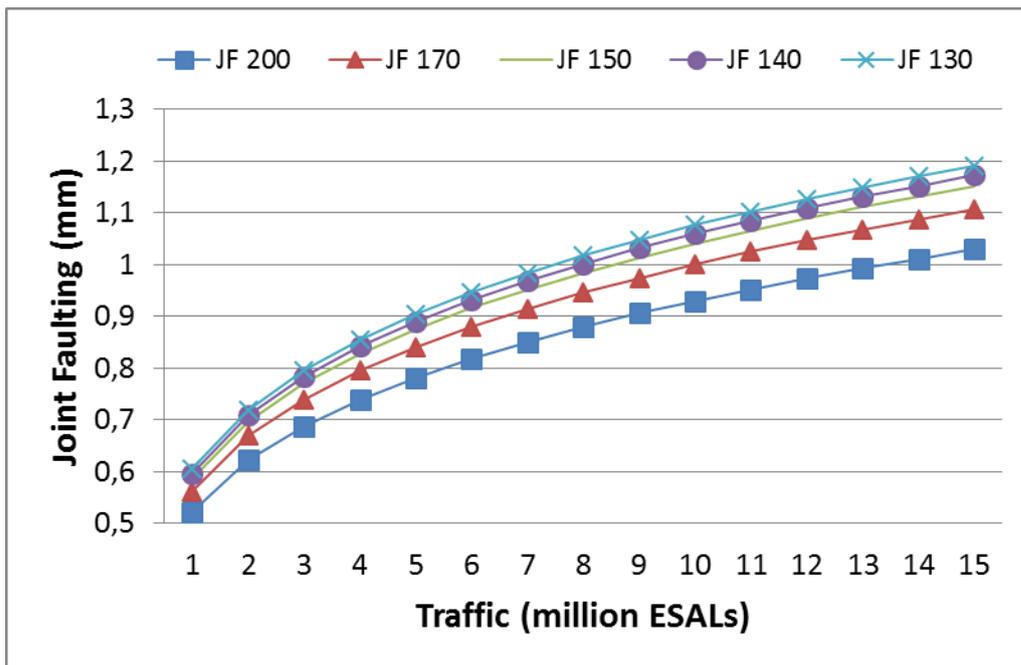


Figure 4. Relation LTE-crack width for traditional and short slabs JPCPs (Reproduced from Pradena and Houben, 2016b by kind permission of STEF92 Technology)

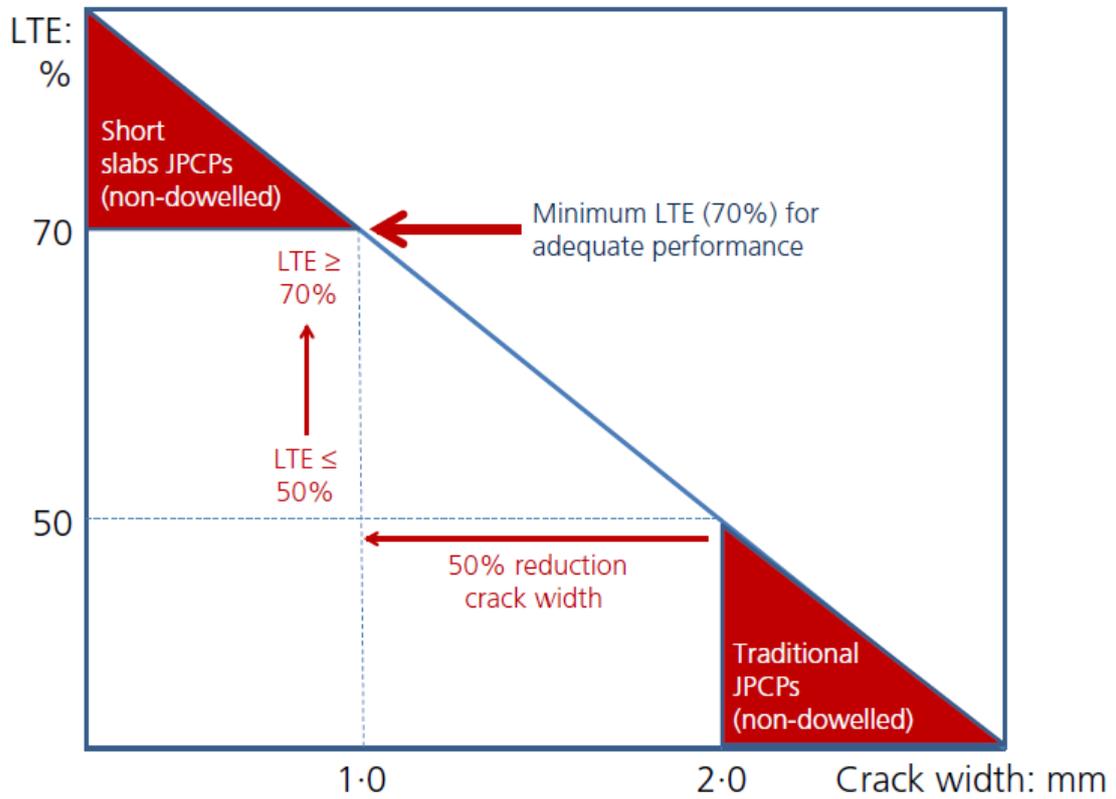


Figure 5. Concrete overlay at a bus lane of Santiago city, Chile (Reproduced from Pradena and Houben, 2015 by kind permission of STEF92 Technology)

