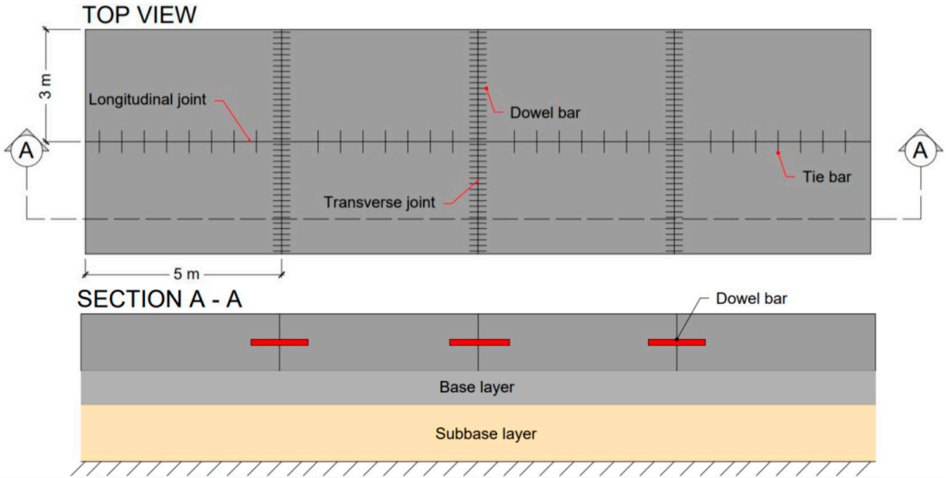
KTH ROYAL INSTITUTE
OF TECHNOLOGY

Licentiate Thesis in Civil and Architectural Engineering

Concrete pavements' repair techniques and numerical assessment of dowel bar load transfer efficiency

SAIMA YAQOOB



Stockholm, Sweden 2024

Concrete pavements' repair techniques and numerical assessment of dowel bar load transfer efficiency

SAIMA YAQOOB

Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Licentiate of Engineering on Tuesday the 12th March 2024, at 1:00 p.m. in room B3, Brinellvägen 23, Stockholm.

Licentiate Thesis in Civil and Architectural Engineering
KTH Royal Institute of Technology
Stockholm, Sweden 2024

© Saima Yaqoob

TRITA-ABE-DLT-2356
ISBN 978-91-8040-808-0

Printed by: Universitetsservice US-AB, Sweden 2024

Abstract

Concrete pavements are a suitable alternative for high-traffic volume roads, concentrated loads and roads exposed to severe weather conditions. In Sweden, among other reasons, the scarcity of concrete pavements is attributed to the need for more national knowledge and expertise in the field. The most recent concrete pavement was constructed seventeen years ago in Uppsala. Concrete pavements are renowned for their longevity and durability. Jointed plain concrete pavements (JPCP) are the most frequent type of concrete pavements. However, it is important to note that the joints in concrete pavements are critical components that can lead to various distresses, necessitating rehabilitation. Rehabilitating concrete pavements is particularly challenging in areas with heavy traffic and requires substitute routes because of the imperative to maintain traffic flow during construction. Developing effective detours might involve significant alterations to the existing routes or building temporary roads, which entails substantial cost investment and time consumption.

A literature review has been conducted to study the available methods that can be used to repair concrete pavements. The strategy for selecting a repair technique is based on rehabilitating the concrete pavement within a short work window, deterring traffic congestion and ensuring the long service life of the pavements. The study showed that the precast concrete technology based on the precast slabs is a promising technology that effectively shortens the lane closure for repairing damaged pavements and produces durable pavements, thereby extending the service life of pavements. However, the construction or rehabilitation cost of concrete pavement using precast slabs is 1.6 to 4 times higher than that of conventional cast-in-place concrete. Therefore, rehabilitation using precast slabs is inappropriate for low-traffic roads and temporary routes.

Joints are crucial for the rehabilitation of concrete pavements with precast slabs. The structural performance of concrete pavement is, however, greatly affected by the joints, as the presence of joints creates a discontinuity between adjacent slabs and thus diminishes the load transfer to the abutting slab. To maintain the structural integrity of the pavement system, dowel bars are used at the transverse joints.

A numerical study has been conducted to evaluate the influence of various dowel-related parameters on the interaction between adjacent concrete slabs. The study revealed that the dowel bar's position, mislocation and diameter had an obvious effect on joint efficiency, while the bond between the concrete slab and the dowel bar slightly affected the load transfer efficiency. It was also investigated that the dowel bar's intended performance, i.e., load transfer efficiency, was reduced as the joint gap between adjacent slabs increased.

Sammanfattning

Betongbeläggningar är ett lämpligt alternativ för högtrafikerade vägar, koncentrerad belastning och vägar utsatta för svåra väderförhållanden. I Sverige är betongvägar sällsynta vilket bl.a. beror på brist på kunskap och kompetens. Den senaste betongvägen byggdes för sjutton år sedan i Uppsala. Betongbeläggningar är kända för sin långa livslängd och hållbarhet. Den vanligaste typen av betongvägar är fogade, oarmerade betongbeläggningar. Ändå är det viktigt att notera att fogarna i betongbeläggningar är kritiska komponenter som kan leda till olika olägenheter, vilket kräver rehabilitering. Att rehabilitera betongbeläggningar är särskilt utmanande i områden med intensiv trafik som kräver ersättningsvägar på grund av nödvändigheten att upprätthålla trafikflödet under reparationsarbetena. Att ta fram en effektiv omledning av trafiken kan innebära antingen väsentliga förändringar och förlängningar av befintliga rutter eller byggande av tillfälliga vägar, vilket medför betydande kostnadsinvesteringar och tidsåtgång.

En litteraturöversikt har genomförts för att studera de tillgängliga metoderna som kan användas för att reparera betongbeläggningar. Strategin för valet av reparationsmetod bygger på att rehabilitera betongbeläggningen inom ett kort arbetsfönster, förhindra trafikstockningar och säkerställa lång livslängd för beläggningen. Studien visade att förtillverkade betongplattor är en lovande metod som effektivt förkortar avstängningen av körfält för att reparera skadad beläggning och producerar hållbara betongbeläggningar med lång livslängd. Rehabiliterings kostnaden för betongbeläggning med prefabricerade plattor är emellertid 1,6 till 4 gånger högre än den för konventionell platsgjuten betong. Därför är rehabilitering med förtillverkade betongplattor olämplig för vägar med låg trafik och temporära rutter.

Fogar är vidare nödvändiga vid reparation med förtillverkade betongplattor. Betongbeläggningens strukturella prestanda påverkas dock kraftigt av fogar, eftersom förekomsten av fogar skapar en diskontinuitet mellan intilliggande plattor och därmed minskat lastöverföringen till den angränsande plattan. För att upprätthålla den strukturella integriteten hos beläggningssystemet används dymlingar i de tvärgående fogar.

En numerisk studie har genomförts med olika parametrar för att utvärdera dymlingens inverkan på fogens effektivitet. Studien visade att dymlingens position, felplacering och diameter har en tydlig inverkan på fogens effektivitet, medan vidhäftningen mellan dymling och betongplatta enbart verkar ha en marginell inverkan på fogens effektivitet. Studien visade också att dymlingens prestanda, dvs. lastöverföringsförmågan, minskade då fogöppningen eller glappet mellan två närliggande plattor ökade.

Preface

The research presented in this thesis was carried out at the Division of Concrete Structures within the Department of Civil and Architectural Engineering at the KTH Royal Institute of Technology in Stockholm from March 2021 to March 2024. This research was made possible through financial support from the Swedish Transport Agency (Trafikverket), which is gratefully acknowledged.

I am deeply indebted to my main supervisor, Johan Silfwerbrand, who trusted in me for this project and provided crucial discussions, offered fruitful guidance and drove me towards greater heights throughout the work. My appreciation extends to the assisting supervisor, Larissa Strömberg, for her help and support. I wish to thank Romain Gabriel Roger Balieu at the Division of Structural Engineering and Bridges for his help during the numerical work.

I also address sincere thanks to Mark B. Snyder (PERC, USA) and Shiraz Tayabji (CPTC, USA) for their guidance to my concerns. I am highly thankful to Denis Jelagin at KTH for reviewing the thesis.

A special thanks goes to my departmental colleagues for their encouragement and advice.

Lastly, I am deeply grateful to my beloved family for their endless support.

Stockholm, January 2024

Saima Yaqoob

List of Publications

The thesis includes two journal papers and one peer-reviewed conference paper, which are as follows.

Paper I: Yaqoob, S., Silfwerbrand, J. (2023). Rapid repair of concrete pavement using precast technology. Paper Presented at "14th International Symposium on Concrete Roads, Krakow, Poland, 25-28 June, 16 pp.

Paper II: Yaqoob, S., Silfwerbrand, J., Strömberg, L. (2021), Evaluation of Rapid Repair of Concrete Pavements Using Precast Concrete Technology: A Sustainable and Cost-Effective Solution. Nordic Concrete Research, 65 (2), pp 107-128.

Paper III: Yaqoob, S., Silfwerbrand, J., Balieu, R.G.R. (2023), A parametric study to investigate the dowel bar load transfer efficiency in the jointed plain concrete pavement using a finite element model, Manuscript submitted for publication.

The first author conducted the literature survey, performed numerical simulations and wrote all the papers. The co-authors contributed to the papers with amendments and comments on results and writing.

Other publications within the project

- Yaqoob, S., Silfwerbrand, J., Strömberg, L. (2022). Overnight rehabilaition of concrete pavements using precast concreet technology. Paper presented at XXIV NCR Symposium, Stockholm, Sweden, 16 - 19 August 2022, 4 pp.

Contents

Chapter 1

Introduction

1.1 Background

Pavements play a multifaceted role in social development by contributing to the various aspects of road infrastructures, such as accessibility, mobility, safety and aesthetics. Like other engineered structures, the pavements must be designed to be durable and have a long service life. The well-functioning road network is an integral factor in fostering economic growth. The key function of the pavement is to effectively withstand imposed traffic loads and environmental conditions during severe weather and provide an efficient and smooth ride.

Typically, pavements are classified into two groups, i.e., asphalt (flexible) or concrete (rigid) pavements. Asphalt pavement is composed of bituminous wear (surface) layer, a cement or asphalt-treated base, followed by an unbounded road base, subbase and subgrade. In contrast, concrete pavement's wear (surface) layer consists of Portland cement concrete. When a vehicle load is applied on asphalt pavement, it deforms and bends under the imposed load, potentially overstressing the underlying layers. Conversely, concrete pavements are rigid, distributing stresses to the subbase and subgrade, but are susceptible to flexural stresses. The choice of pavement material depends on various factors, including traffic volume, magnitude of traffic load, maintenance proficiency, environmental considerations, location and intended use of the pavement. The load-carrying capacity of a highway depends not exclusively on the roadway itself, but on the entire pavement system, which consists of various layers. However, due to high rigidity, the concrete pavement layer substantially contributes to the load-carrying capacity. The load distributions of asphalt and concrete pavements are shown in Figures 1.1 and 1.2.

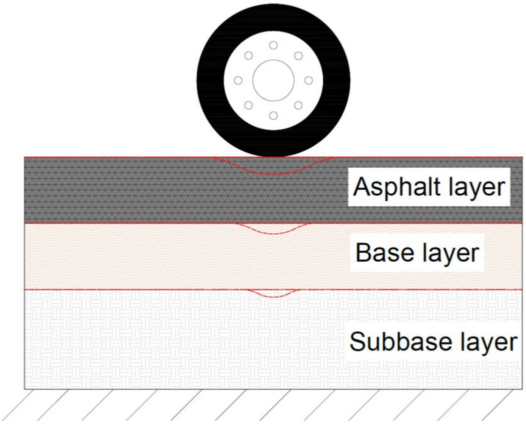


Figure 1.1: *An illustration of load distribution in asphalt pavement.*

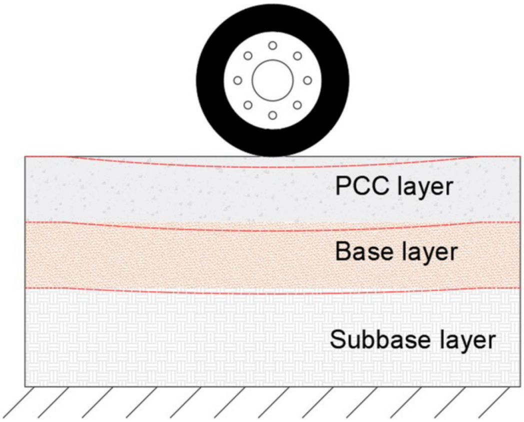


Figure 1.2: *An illustration of load distribution in concrete pavement.*

Concrete pavements' durability, longevity and capacity to endure heavy loads make them a valuable asset for the nation's road network. The concrete's rigid nature also makes the roads resilient to both high and low temperatures. Concrete pavements are prevalent in the United States and several European countries but are not widely adopted in Sweden. Despite the total length of Swedish motorways exceeding 2100 km, only 67 km consists of concrete roads (Silfwerbrand, 2023; Strömberg et al., 2020). The lack of concrete pavement in Sweden is discussed in papers I and II, with key points summarised as follows (Silfwerbrand, 2014, 2016, 2023):

- The construction expenses of concrete pavements exceed the corresponding asphalt pavements' costs. Therefore, asphalt pavements are considered a more economical option.

- In Sweden, the construction of concrete roads is more costly due to the lack of Swedish slip-form pavers. The paved concrete pavement has involved subcontractors from the Netherlands and Germany.
- The results of the most recent Swedish concrete pavement, particularly the premature wearing on Uppsala and Eskilstuna highways, have not been auspicious (see Section 2.10).
- The client's concern revolves around the potential occurrence of major deteriorations. There is apprehension that addressing these issues might necessitate prolonged road closures and create long detours for road users.

1.2 Types of concrete pavements

Concrete pavements exist in various types, i.e., jointed plain concrete pavement, joint reinforced concrete pavements, continuously reinforced concrete pavements, roller compacted concrete pavements and concrete overlay or white toppings. Each type is briefly discussed below.

1.2.1 Jointed plain concrete pavements

The jointed plain concrete pavement (JPCP) is the most common type of concrete pavement used internationally. In JPCP, longitudinal and transverse joints are deliberately created at regular intervals. Longitudinal joints are oriented parallel to the traffic direction, while transverse joints are aligned perpendicular to the traffic direction. These proposed joints aim to avoid shrinkage cracks and accommodate the expansion and contraction of the concrete slab due to temperature alterations. JPCP does not incorporate any reinforcement within the concrete slab. However, the existence of joints causes irregularities between the adjoining slabs. Therefore, transverse joints play a crucial role in JPCP, significantly influencing the performance of the concrete pavement. To enhance structural integrity, dowel bars are installed in the direction of traffic. The key role of the dowel bar is to distribute the traffic load across the joints. Additionally, the dowel bar prevents the differential movement of abutting slabs (Selvam et al., 2023; Caltrans, 2015). A schematic view of jointed plain concrete pavement is shown in Figure 1.3.

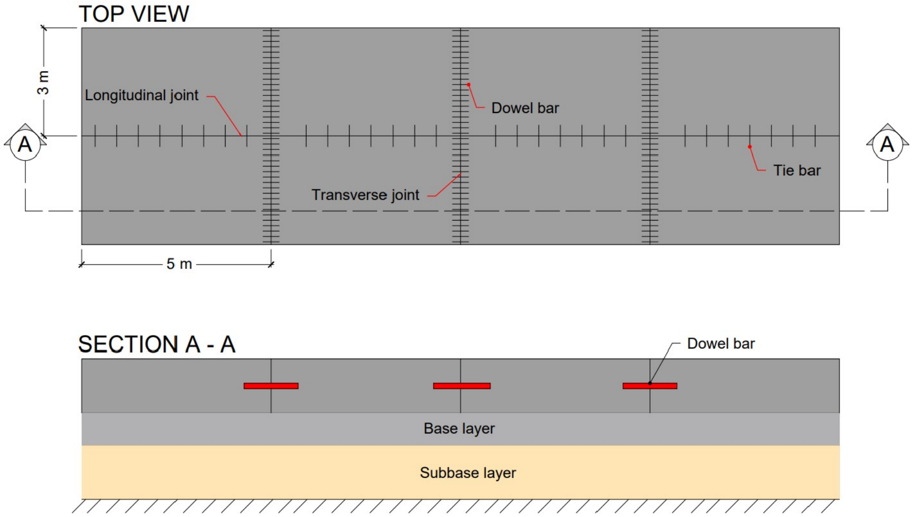


Figure 1.3: *Top and sectional view of jointed plain concrete pavement.*

1.2.2 Joint reinforced concrete pavements

As the name implies, the joint reinforced concrete pavements (JRCP) incorporate both joints and steel reinforcement (within the slab). The concrete slabs in JRCP are comparatively longer than in JPCP. The steel content typically ranges between 0.10 and 0.25 percent of the cross-sectional area, with a higher concentration of steel along the traffic direction and a lower amount in the transverse direction (Delatte, 2008). The primary function of steel is to keep the cracks together and maintain aggregate interlocking. However, the steel reinforcement ends at the transverse joint location and dowel bars are implemented to preserve the structural effectiveness of the pavement system (Syed, 2021). Figure 1.4 shows the schematic view of joint reinforced concrete pavement.

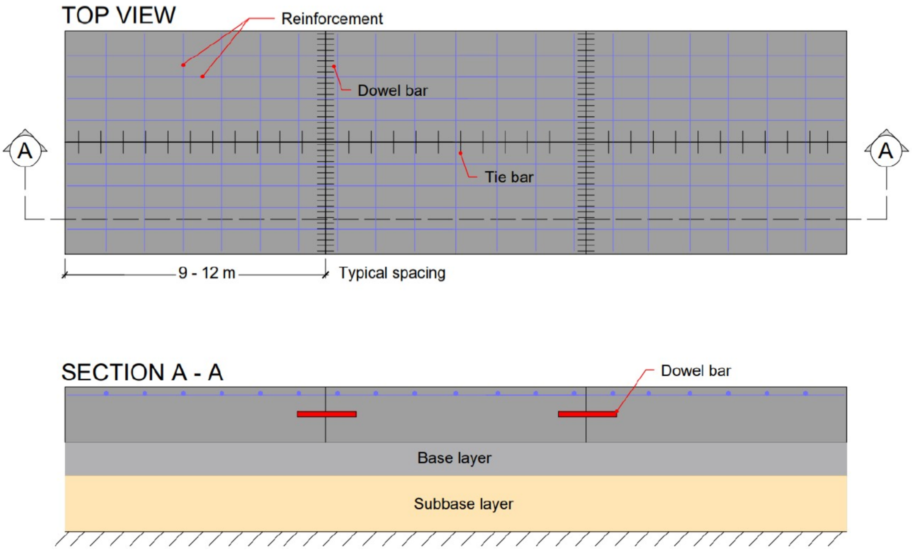


Figure 1.4: *Top and sectional view of joint reinforced concrete pavement.*

1.2.3 Continuously reinforced concrete pavements

The continuously reinforced concrete pavements (CRCP) have no joints except at the transition to the other pavement structures or at bridges. The CRCP consists of longitudinal reinforcement with a sufficient lap splice to ensure reinforcement continuity, while additional reinforcement is provided in the transverse direction to support the longitudinal reinforcement. The amount of longitudinal reinforcement typically ranges between 0.70 and 0.75 percent (milder to harsher climate). The purpose of the design reinforcement content is to prevent distresses caused by structural and environmental loading and provide equilibrium between crack spacing and crack width at the time of opening of cracks. CRCP presents a remarkable, durable solution with maintenance-free service life for heavily loaded roads (Roesler et al., 2016; Plei and Tayabji, 2012; Tayabji and Plei, 2019). The schematic view of continuously reinforced concrete pavement is shown in Figure 1.5.

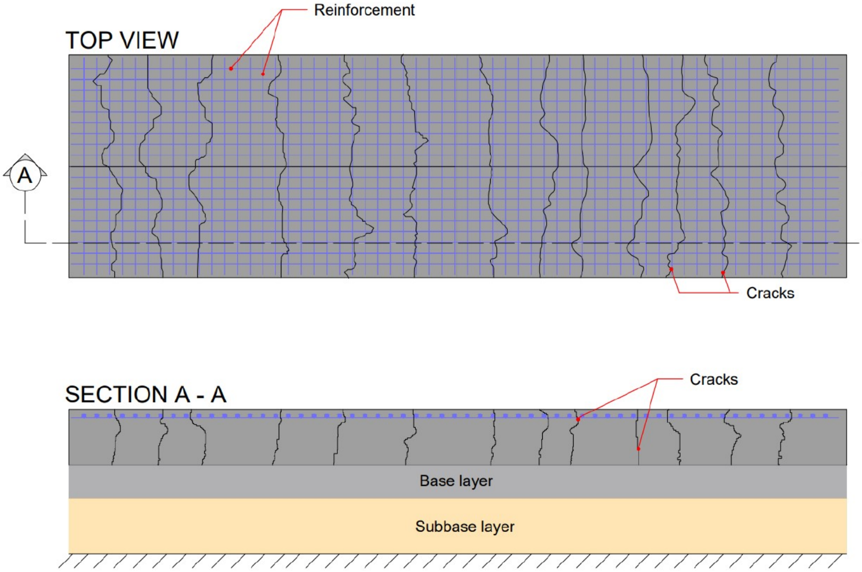


Figure 1.5: *Top and sectional view of continuously reinforced concrete pavement.*

1.2.4 Roller compacted concrete pavements

The roller compacted concrete (RCC) is a product of low water content (zero slump) conventional concrete. RCC pavements are only suitable for roads that carry heavy loads in low-speed areas and are typically placed with an asphalt-type paver. RCC pavements are viable for various applications, such as ports, highway shoulders, streets, highways and military bases (Harrington et al., 2010; ACI327R-14, 2015; ACPA, 2014; Zollinger, 2016; Bauchkar and Chore, 2012). RCC exhibits low shrinkage (0.10 - 0.15 per mile), enabling the construction of pavements without joints (Silfwerbrand, 1995). Nevertheless, if joints are selected to enhance pavement cracking control, they are usually spaced at greater intervals than conventional concrete pavements and are built without dowels (Harrington et al., 2010). RCC pavements are cost-effective as they reduce construction costs by 10 to 30 percent compared to conventional concrete pavements (Shoenberger, 1994).

1.2.5 Concrete overlay or Whitetoppings

The white topping consists of a concrete wear layer on the existing asphalt layer, typically used to repair rutted asphalt roads. The white topping consists of a thinner slab than conventional Portland cement concrete pavements. Based on thickness, white topping is classified into three categories, i.e., Conventional white topping (WT), Thin white topping (TWT) and Ultra-thin white topping (UTWT).

The overlay thickness of WT is equal to or greater than 200 mm (8 in.), TWT thickness ranges between 100 and 200 mm (4 - 8 in.) and the UTWT consists of slab thickness less than 100 mm (4 in.) (Lawal, 2022; Rasmussen and Rozycki, 2004; Gucunski, 1998; Mateos et al., 2015). The design thickness of the white topping is dependent on the support conditions of the underlying asphalt layer. The performance of white topping is greatly influenced by slab thickness, joint layout and support conditions provided by the existing asphalt layer (Kim et al., 2007; Silfwerbrand, 1995).

1.3 Problems

The heavy trafficked loads, climate conditions and temperature variations in the surrounding environment can considerably affect the structural integrity of concrete pavements. As a result, rehabilitation is required to prevent the pavement system's deterioration, ensure safe driving and extend the pavement's service life. Repairing concrete pavement with cast-in-place concrete can be quite challenging, especially for high-traffic-volume roads, as it typically requires several days of lane closures to make the rehabilitated pavement ready for traffic operations.

Prolonged lane closure on the high volume trafficked roads causes disruptions and inconveniences for road users - as the fewer available lanes lead to slower traffic flow, longer travel times and increased traffic congestion, which becomes more pronounced, particularly during peak hours. Implementing temporary detours or alternative routes may be necessary to alleviate traffic congestion and minimize the impact on commuters. It is important to recognize that these approaches can be expensive and time-consuming.

1.4 Aims and goals

This thesis aims to compile the techniques that can be used to repair concrete pavements rapidly and evaluate the response of concrete pavement due to various dowel-related parameters. Dowel bars constitute an important part of the structural performance when connecting replacing slabs to the existing pavements. During the literature review of precast concrete slabs used for concrete pavement repair, it was observed that the location of dowel bars varies among studies. Some studies reported the location in the top of the slab, while others preferred at the bottom or at mid-height. However, ensuring good structural performance necessitates placing the dowel bar in the appropriate location.

The goal of the thesis is addressed in the following research questions:

- **Repair technique (Papers I & II)**
    - Which method is suitable for rehabilitating the concrete pavements in order to minimise the lane closure duration, prevent traffic congestion and result in long-lasting and durable pavements?
- **Assessing dowel bar effectiveness for load transfer (Paper III)**
    - Can the dowel bar's position, mislocation and size affect the interaction between adjacent concrete slabs?
    - Does the joint opening impact the load transfer efficiency?
    - Does the bond between the concrete slab and dowel bar influence the load transfer efficiency?

1.5 Limitations

- The research has been limited to focusing on the jointed plain concrete pavement, as it is the most common concrete pavement system in Sweden.
- The damaged concrete pavements might require partial or full-depth repair; this study deals with full-depth repair.
- In jointed plain concrete pavements, load transfer occurs either through aggregate interlocking or steel dowel bars. This study is confined to the dowel bar load transfer system.
- From the beginning of the research, it was decided to conduct a full-scale test to repair the damaged highway using precast slabs according to Swedish standards. However, Trafikverket (The Swedish Transport Administration) could not provide the experimental site.

1.6 Outline of the thesis

Chapter 2 discusses common deteriorations in concrete pavements. In Chapter 3, the research methods upon which the thesis is based are presented, including a literature survey and numerical simulation. Chapter 4 discusses the techniques that can be used to repair damaged concrete pavements. The results from the literature and numerical studies are presented in Chapter 5. The findings from the literature review and numerical simulations are discussed in Chapter 6. Chapter 7 presents the answers to the research questions as well as suggestions for future work.

Chapter 2

Distresses in concrete pavements

Pavement distresses in this chapter refer to various damages or imperfections that can emerge on a pavement structure's surface over time. Deterioration occurs due to a combination of factors, including the effects of traffic loads, environmental conditions and material used in the pavement. These distresses can negatively impact the pavement's performance, durability, safety and aesthetics. Some common types of concrete pavement distresses are longitudinal cracking, transverse cracking, corner cracking, spalling, scaling, faulting, pumping, joint seal damage, blowup and rutting.

2.1 Longitudinal cracking

Longitudinal cracking in concrete pavement refers to cracks that develop parallel to the direction of traffic flow; see Figures 2.1 and 2.2. Several factors can lead to longitudinal cracks, i.e., frost heave, erosion, timing of joint saw cuts (too early or too late), depth of joint sawing, joint failures, imposed traffic loading, heavy number of load repetitions and environmental loading.

Once the crack appears on the pavement surface, it can eventually lead to multiple parallel cracks either at an early age or during the operational lifespan (Harrington et al., 2018). The longitudinal cracks are divided into three categories based on the severity levels, i.e., low, moderate and high (Harrington et al., 2018; Miller et al., 2014).

- **Low**: Crack widths $<$ 3 mm [0.125 in.] with unquantifiable faulting, no flaking or spalling, or securely sealed with indeterminate width.
- **Moderate**: Crack widths that range between 3 mm [0.125 in.] and 13 mm [0.5 in.] or spalling $<$ 75 mm [3 in.] and faulting not exceeding 13 mm [0.5 in.].
- **High**: Crack widths $>$ 13 mm [0.5 in.], or with spalling $>$ 75 mm [3 in.] or faulting $>$ 13 mm [0.5 in.].

Figure 2.1: *Longitudinal cracking crossing the transverse joint in JPCP (Harrington et al., 2018).*

Figure 2.2: *Longitudinal cracking due to delayed sawing in JPCP (Harrington et al., 2018).*

2.2 Transverse cracking

Cracks oriented perpendicular to the pavement centreline are known as transverse cracking; see Figure 2.3. These cracks form due to temperature variations, shrinkage, inadequate slab thickness and saw cut depth, the timing of joint saw cuts (too early or too late), the intensity of traffic load, the number of vehicle repetitions, improper joint spacing and joint lockup. Transverse cracks' severity is categorised into three groups, i.e., low, moderate and high (Harrington et al., 2018; Miller et al., 2014).

- **Low**: Crack width < 3 mm [0.125 in.] with unquantifiable faulting, no flaking or spalling, or securely sealed with indeterminate width.
- **Moderate**: Crack width that ranges between 3 mm [0.125 in.] and 6 mm [0.25 in.], or with spalling 75 mm [3 in.] and faulting not exceeding 6 mm [0.25 in.].
- **High**: Crack width > 6 mm [0.25 in.], or with spalling > 75 mm [3 in.] and faulting not exceeding 6 mm [0.25in.].

Figure 2.3: *Illustration of transverse cracks on JPCP (Harrington et al., 2018).*

2.3 Corner cracking

A corner break or corner cracking is a crack that intersects the adjoining joints (i.e., the longitudinal and transverse joint at an angle of approximately 45°) along the traffic direction. Each side must be at least 300 mm (12 inches) long and can extend to half the width of the slab; see Figure 2.4. Corner cracking occurs due to shrinkage, erosion, pumping, poor load transfer at the transverse joint and joint lockup; for details, see Shahin (2009) and Harrington et al. (2018). Corner cracking is quantified by counting the number of existing cracks. A photo of corner cracking in a concrete pavement is presented in Figure 2.5.

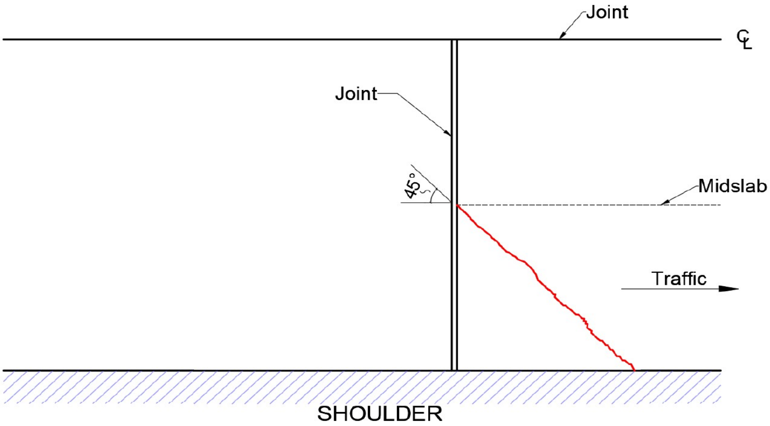


Figure 2.4: *An illustration of corner cracking redrawn from Miller et al. (2014).*

Figure 2.5: *Corner cracks in concrete pavement (National Concrete Pavement Technology Center (used with permission)).*

2.4 Spalling

Spalling is the cracking, breaking, and chipping along the edges of a concrete slab, typically within 0.3 m [1 ft] from the face of longitudinal and transverse joints. Spalling initiates in the top surface of the slab and can extend further down into the depths. Spalling differs from corner cracking in that it involves surface damage, whereas, in corner cracking, the crack extends vertically through the entire slab depth. The consequence of spalling may include roughness, small vertical troughs and loose debris on the pavement surface. The severity of spalling can be categorized into low, moderate, and high levels (Harrington et al., 2018).

Figures 2.6, 2.7 and 2.8 present the spalling due to the incompressible joint damage, heavy loads and misaligned dowel bar, respectively.

- **Low**: Spalls with a width < 75 mm [3 in.] measured from the face of the joint and without any associated patching, irrespective of whether the material loss is present and without any associated patching.
- **Moderate**: Spalls range between 75 and 150 mm [3 - 6 in.] measured from the face of the joint, with material loss.
- **High**: Spalls > 150 mm [6 in.] measured from the face of the joint, including the material loss and spalls fractured into pieces or spalls containing the patching.

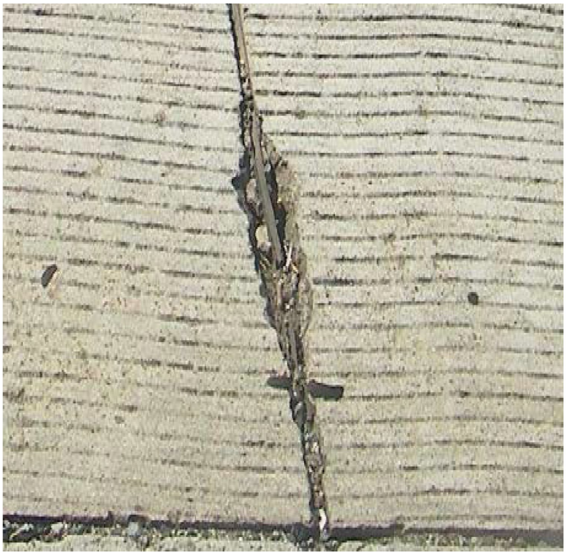


Figure 2.6: *Spalling due to incompressible joint damage (Harrington et al., 2018).*

Figure 2.7: *Spalling from heavy loads (Harrington et al., 2018).*

Figure 2.8: *Spalling due to misaligned dowel bar (Harrington et al., 2018).*

2.5 Scaling

Scaling is the flaking of hardened concrete surfaces, as shown in Figure 2.9. It typically occurs on the upper surface of the concrete slab and can vary in thickness, ranging between 3 mm and 13 mm. Scaling can manifest at various locations across the pavement's top layer. Typically, too little entrained air causes scaling- as adequate air entrainment is required to protect against freezing and thawing damage.

Figure 2.9: *Scaling (National Concrete Pavement Technology Center (used with permission)).*

2.6 Faulting

The difference in the elevation between adjacent concrete slabs is known as faulting; see Figure 2.10. Faulting can occur due to the loss of materials under the trailing slab or the settlement of the concrete slab. Additionally, traffic loads and improperly sealed joints can lead to joint faulting - as traffic loads induce cracks and spalling at joints in concrete pavement, while poorly sealed joints provide channels for water intrusion, resulting in the saturation of the underlying layer. According to Khazanovitch et al. (2009), the corroded dowel bar system promotes faulting by diminishing the load transfer capacity between adjacent slabs.

Over time, faulting becomes more pronounced, worsening the ride degradation. To mitigate faulting, it is crucial to implement the effective designs for the base, subdrainage, joint load transfer and spacing. Faulting is classified into different levels of severity, namely low, moderate and high, based on the following criteria (Harrington et al., 2018):

- **Low**: Faulting not exceeding 3 mm [0.125in.]
- **Moderate**: Faulting ranges between 3 mm and 9.5 mm [0.125 and 0.375 in.]
- **High**: Faulting > 9.5 mm [0.375 in.]

Figure 2.10: *Faulting in JPCP (National Concrete Pavement Technology Center (used with permission)).*

2.7 Pumping

Pumping is the process in which water forces the expulsion of material through joints. When a concrete slab undergoes traffic loading, it deflects and causes accumulated water underneath the slab to be pushed out via joints, carrying along fine particles of sand and gravel, lacking pavement support. The curling or warping of the concrete slab due to temperature variations and moisture gradients also contributes to the pumping. The pumping risk can be minimised by properly sealed joints and installing a proper drainage system in the subbase or subgrade - as inadequate drainage increases the possibility of erosion due to pumping and ultimately results in faulting. The pumping mechanism is depicted in Figure 2.11 (Harrington et al., 2018).

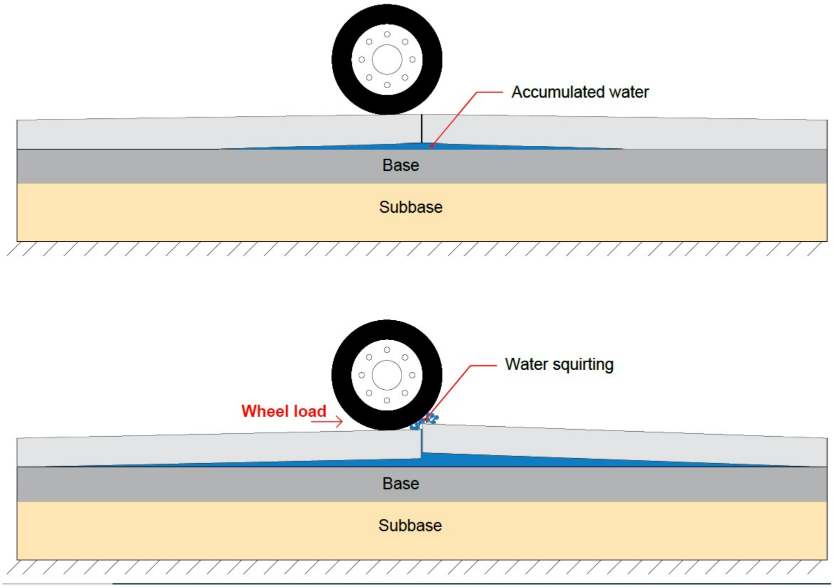


Figure 2.11: *Schematic view of pumping mechanism in JPCP redrawn from Harrington et al. (2018).*

2.8 Joint seal damage

Joint seal damage allows water and incompressible material from the pavement surface to infiltrate the joint. The damage includes sealant bonding, splitting, extrusion and hardening, the incursion of external material into the joint, and loss of sealant. Joint seal damage can result in structural weakening, diminishing load transfer capacity and increased vulnerability to erosion and faulting (Miller et al., 2014).

2.9 Blowup

Concrete slabs expand when exposed to high temperatures, and joints in the pavement are designed to accommodate this expansion. During winter, concrete slabs tend to contract, resulting in wider joint gaps. When these gaps are filled with incompressible materials, the subsequent expansion of the concrete slabs during hot weather can generate significant compressive stresses. If these stresses are not relieved, the slab edges can locally move upward, or shattering can occur in the vicinity of joints, a phenomenon known as blowup. The blowup in JPCP is illustrated in Figure 2.12.

Figure 2.12: *An illustration of blowup in JPCP (Harrington et al., 2018).*

2.10 Rutting

Rutting is the formation of surface depressions or grooves along the wheel path. The primary cause of rutting in concrete pavements is studded tires (Brunette and Lundy, 1996; Cotter and T., 2010). When it rains, the rutted surface poses safety risks, generating a layer of water between the tire and the road surface. Consequently, the vehicle may experience hydroplaning or loss of steering. Additionally, scraping surface materials from studded tires produces dust, contributing to air pollution (Zubeck et al., 2004). An illustration of rutting on JPCP due to studded tires is presented in Figure 2.13.

Figure 2.13: *Rutting due to studded tires in JPCP used with permission of Ellen Dolk (Hultqvist and Dolk, 2014).*

Rutting is a significant challenge on Swedish concrete highways due to the use of studded tires during winter (i.e., November to April) (Löfsjögård and Karlsson, 2004), which demands early rehabilitation (Dolk, 2017). In Sweden, rutting is usually limited to 1 mm/year and grinding is performed after 15 years (Silfwerbrand, 2023). Figure 2.14 presents rutting measurements for Swedish highways, including Arlanda, Falkenberg N, Falkenberg S, Eskilstuna, and Uppsala, constructed in 1990, 1993, 1996, 1999, and 2006, respectively. However, as depicted in Figure 2.14, Uppsala's highway exceeded the anticipated rutting. By the 11th year, the highway was overlaid with asphalt due to excessive rutting.

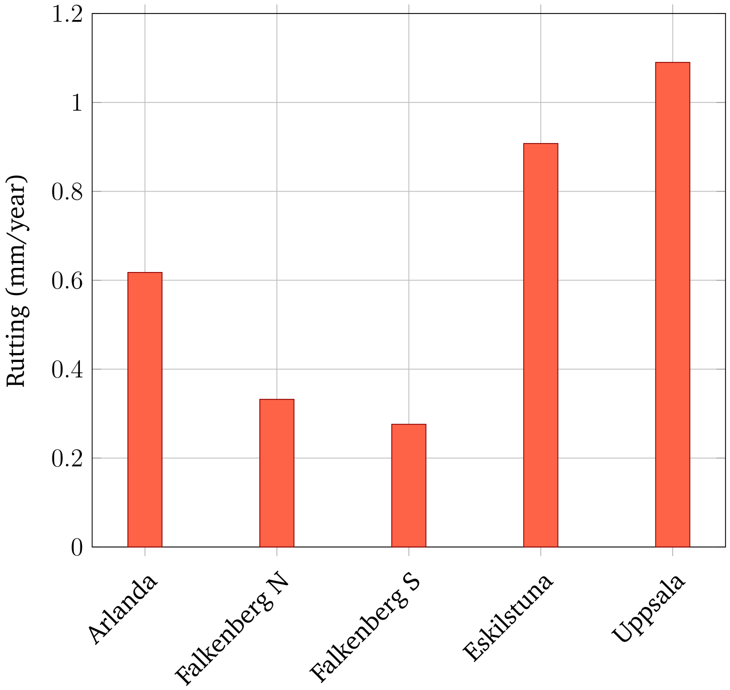


Figure 2.14: *Rutting measured in 2015 redrawn from Silfwerbrand (2023).*

Chapter 3

Methods

This chapter summarises the methods upon which the thesis is built, which includes a literature review and a numerical study.

3.1 Literature review

The extensive repair of concrete pavements in areas with heavy traffic flow poses considerable challenges. A literature review was conducted to explore methods that can be used to rehabilitate concrete pavement during short lane closures, with the goal of minimising traffic disruption and ensuring long-lasting pavements. The literature study includes internet searches, scholarly websites and contacts with experts (Tom Kazmierowski from Canada, Mark Snyder and Shiraz Tayabji from the United States). I also attended the "12th International Conference on Concrete Pavements" in 2021, which was also helpful in accessing the literature.

3.2 Numerical simulation

In the jointed plain concrete pavement system, the load across the joints can be transferred via aggregate interlocking (the irregular faces of adjacent slabs interlock with each other) or steel dowel bars, see Figure 3.1. The numerical simulation investigated the efficiency of interaction between slabs in terms of load transfer capacity, considering dowel-related parameters.

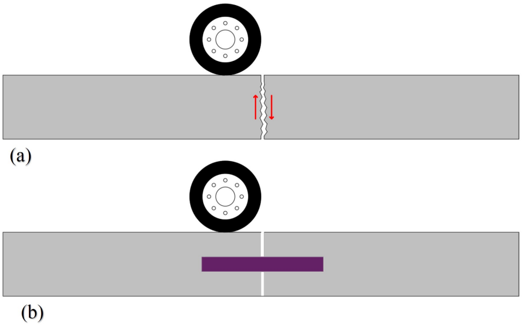

(a)
(b)

Figure 3.1: *Load transfer mechanism in JPCP (a) Aggregate interlocking redrawn from FHWA (2019) (b) Steel dowel bar load transfer system.*

The finite element model used four layers of the pavement system, i.e., the top layer was the concrete slab, while the underlying layers were base, subbase, and subgrade, respectively. The joint opening between adjacent concrete slabs was considered 2 mm and the slabs were connected via 32 mm steel dowel bars, while dowel bars were placed at the centre of the concrete slab, see Figure 3.2. Isotropic materials were considered for the pavement system and the tangential behaviour was considered between the concrete slab and steel dowel bar and among all the layers of the pavement system. At the bottom of the subgrade, all degrees of freedom were restrained and the model comprised of eight-nodded continuum of three-dimensional brick elements.

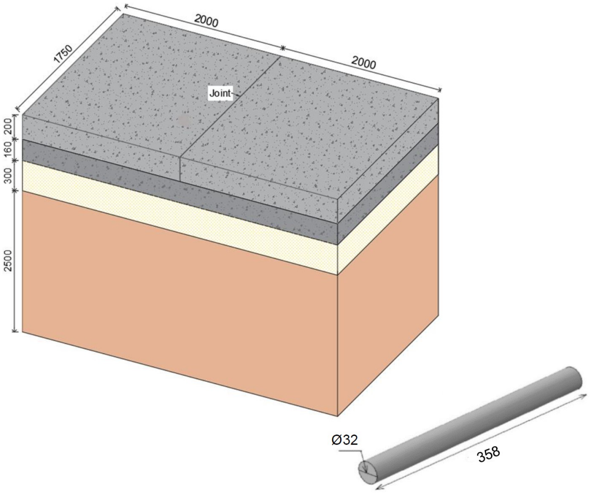


Figure 3.2: *3D view of JPCP, with dimensions given in millimetres (Adapted from Paper III).*

Chapter 4

Techniques to repair concrete pavements

The literature study showed that available techniques for rehabilitating concrete pavements include asphalt overlay, in-situ rapid-strength developing concrete and precast concrete technology.

4.1 Asphalt overlay

The asphalt overlay serves as a protective shield for the underlying concrete layer, reducing temperature and moisture variations and mitigating deformations caused by the curling and warping of concrete slabs (see Section 4.2). However, the performance of the overlay is greatly affected by reflective cracking, which can result in various deteriorations, including spalling, reduced fatigue life and ride quality (Abut and Gür, 2023; Zhang and Khattak, 2019). The reflective cracks in the overlay develop due to traffic and thermal loading, progressing through two distinct stages: (i) crack initiation - in this stage, the crack originates at the joint or crack of existing pavement and (ii) crack propagation - in this stage, the crack further extends to the surface of the overlay. The traffic load contributes to crack initiation, while the thermal load leads to crack propagation (Zhang and Khattak, 2019). According to Lytton (1989), when traffic loads pass over the crack in the existing pavement, they induce three critical stress pulses, including one maximum bending and two maximum shear stresses; see Figure 4.1. The thermal stresses in the overlay are a consequence of temperature variations at the surface and the expansion and contraction of existing damaged pavement; see Figure 4.2.

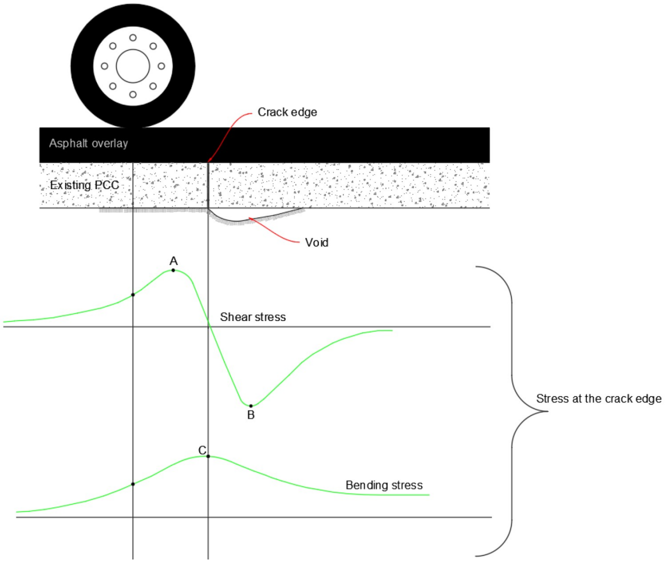


Figure 4.1: *Traffic induced stresses in the overlay redrawn from Lytton (1989).*

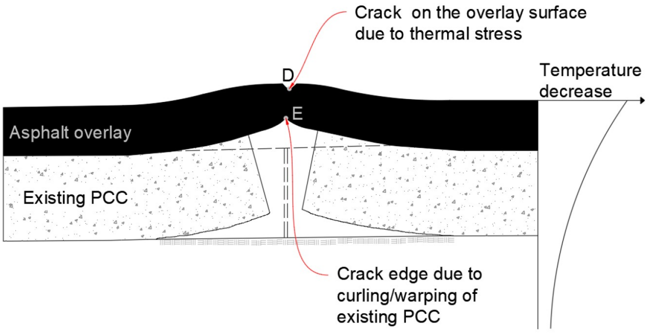


Figure 4.2: *Crack growth in the overlay due to temperature changes redrawn from Lytton (1989).*

4.2 In-situ rapid strength developing concrete

Rapid strength concrete is also known as fast-setting concrete (ACPA, 1994). In-situ rapid strength developing concrete can be used for both partial and full-depth repairs.

- **Partial depth repair**: Partial-depth repair is used to repair small patches or localized distresses, such as spalling or severe scaling in the concrete pavement (Frentress and Harrington, 2011). The size of a partial depth patch is typically 1 m^2 [1.2 sq. yd], while the patch can range from a few millimetres to one-half of the pavement depth. Partial depth repair can only be applied to the spalling caused by the corrosion of dowel bars if it is possible to replace the existing dowel bar, yet the spall should not be deeper than one-half of the slab thickness (ACPA, 1998). The cost of partial-depth repair is primarily influenced by factors such as the repair area's location, size and the number of patches. Figure 4.3 shows the schematic view of partial-depth repair.

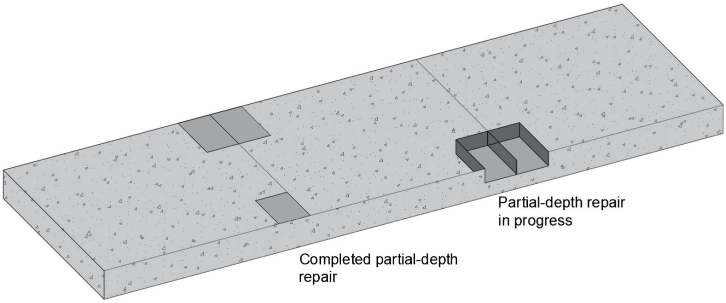


Figure 4.3: *Schematic view of partial-depth repair redrawn from ACPA (1998).*

- **Full depth repair**: In full-depth repair, individual damaged concrete slabs are entirely replaced. Joint deterioration at the transverse or longitudinal side, longitudinal and transverse cracking, corner break and blowup are the common distresses in jointed plain concrete pavement, which requires full-depth repair (ACPA, 1995). The severity of each distress is presented in Table 4.1. A schematic view of full-depth repair is depicted in Figure 4.4.

Table 4.1: *Distress type and severity in jointed plain concrete pavement (ACPA, 1995).*

Distress	Severity
Longitudnal cracking	High with faulting ≥ 12 mm [0.5 in.]
Transverse cracking	Medium with faulting ≥ 6 mm [0.25 in.]
Joint deterioation	Medium with faulting ≥ 6 mm [0.25 in.]
Durability	Medium
Corner break	Low
Blowup	Low

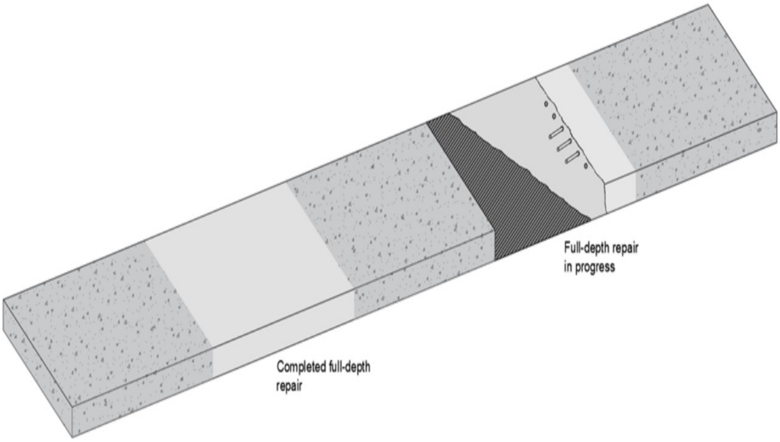


Figure 4.4: *Schematic view of full-depth repair redrawn from ACPA (1995).*

Rapid strength is typically achieved by altering the mix design and incorporating the special admixtures. Due to admixtures, rapid-strength concrete is greatly affected by environmental changes. The two most important environmental factors that affect rapid-strength concrete are temperature and moisture gradient, which can lead to curling and warping. According to Ceylan et al. (2016), curling is deformation resulting from a non-uniform temperature gradient. In contrast, warping is deformation resulting from a non-uniform moisture gradient. The temperature-induced slab deflection follows a diurnal pattern, while the warping effect follows seasonal variation (Chang et al., 2008; Rao et al., 2001).

During the early stage, rapid-strength concrete is particularly prone to deformations due to its low resistance against applied loads. Drying out at this stage can lead to premature cracking. Curling or warping causes the concrete slab to lose support either in the middle or at the edges and as a consequence, the self-weight of the slab exerts tensile stress at the bottom and top. Furthermore, the upward lifting of the slab can lead to the widening of joints between adjacent slabs (Ceylan et al., 2016).

Hansen and Wei (2008) conducted a laboratory test on two concrete beams for each case, imitating the conditions of the existing field slab to measure the influence of uplift. The two cases studied were: (i) drying at the top and bottom with sealing and (ii) drying at the top with saturation at the bottom (water present at the base). Their findings indicated that the uplift was more pronounced in the beam with a saturated bottom; see Figure 4.5.

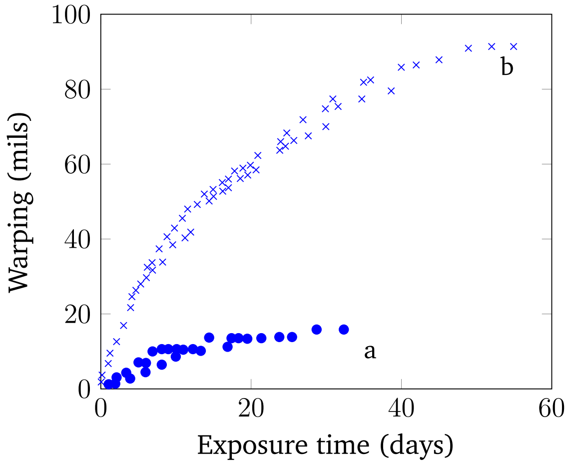


Figure 4.5: *Warping uplift measurement for two cases (a) Drying at the top only (b) Drying at the top and wetting at the bottom redrawn from Hansen and Wei (2008), [1 mil=0.0254 mm].*

4.3 Precast concrete technology

In this technique, high-quality materials are used in a controlled environment to manufacture durable precast slabs. Precast technology expedites construction processes, reducing lane closure durations in densely congested traffic corridors while maintaining high quality and durability standards.

Since 2001, the jointed precast concrete pavement (JPrCP) has been used for more than 113 lane miles (180 lane km), covering approximately 185 projects across 26 states in the United States and two provinces in Canada. Most of these slabs were installed during a nighttime work window of 8 hours or less. However, on some projects, the work duration was limited to five hours, with the work area confined to one lane and an adjacent shoulder. Figures 4.6 and 4.7 illustrate the cumulative use of precast slabs in the United States and Canada through 2018, demonstrating that this technique is the best repair technology for concrete pavements. More details about this technology can be found in Paper II.

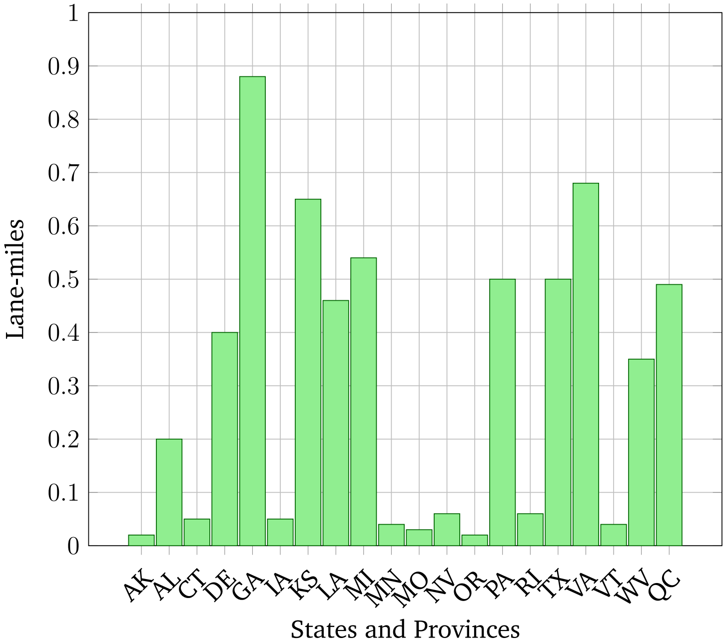


Figure 4.6: *Concrete pavement repair with JPrCP in the United States and Canada under 1 lane mile (1.6 lane km) of JPrCP redrawn from Smith and Snyder (2019).*

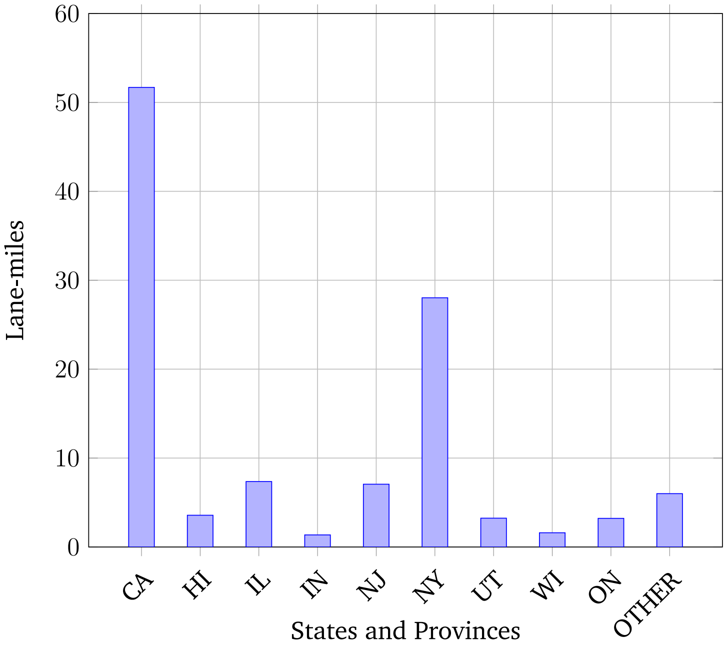


Figure 4.7: *Concrete pavement repair with JPrCP in the United States and Canada over 1 lane mile (1.6 lane km) redrawn from Smith and Snyder (2019).*

Chapter 5

Results

This chapter is divided into two subsections. Section 5.1 provides a summary of repair techniques from Papers I and II, while Section 5.2 covers the results of the numerical study based on Paper III.

5.1 Results from literature review

A literature review was conducted to examine the rapid repair techniques for damaged concrete pavements. The findings indicate that asphalt overlay, rapid-strength cast-in-place concrete and precast concrete technologies have been recognized as effective repair methods. However, it is important to note that the asphalt overlay and rapid-strength cast-in-place concrete can offer rapid repairs but they may not always deliver the same level of durability as precast slabs. Precast concrete technology, particularly, is noteworthy for its ability to produce durable pavements. The literature review also evaluated case studies in Paper II related to precast concrete technology, highlighting the significant reduction in repair time.

5.2 Results from FE analysis

The FE analysis was conducted to study the performance of concrete pavement for various effective dowel-related parameters, including dowel bar position, dowel bar diameter, mislocation of dowel bar, joint opening and bond between the concrete slab and dowel bar. Three different positions of the dowel bar, i.e., top (h= 50 mm), bottom (h= 100 mm) and centre (h= 150 mm) of the slab were considered from the pavement surface. The study incorporated dowel bar diameters of 20 mm, 25 mm, 32 mm, and 38 mm. The mislocation of the dowel bar was assessed in terms of horizontal, vertical, and longitudinal translations. Two cases were investigated for horizontal translation; in the first case, the dowel bar was considered 250 mm from the corner, while in the second case, the dowel bar was placed 350 mm from the corner. In vertical translation, the dowel bar was shifted 25 mm from its planned position. For longitudinal translation, the centroid of the dowel bar was moved 50 mm from its intended location. Different values of joint openings, i.e., 2 mm, 4 mm, 6 mm, 8 mm, 10 mm and 12 mm were considered. Furthermore, the effect of the bond between the concrete slab and dowel bar on load transfer was evaluated by considering different coefficients of friction, i.e., 0.05, 0.5 and 1. The load transfer efficiency was determined by computing the slabs' deflections across the joint and the results are summarised in Table 5.1.

Table 5.1: *Load transfer efficiency for different parameters based on Paper III*

Parameters	Values	Deflection		LTE [c]
		$\triangle$[a]$_{l}$	$\triangle$[b]$_{u_l}$	
	(mm)	(mm)	(mm)	(-)
Dowel bar's position	h= 50	0.3462	0.3234	0.934
	h= 100	0.3459	0.3241	0.937
	h= 150	0.3028	0.2815	0.929
Dowel bar diameter	20	0.3484	0.3191	0.916
	25	0.3472	0.3218	0.927
	32	0.3459	0.3241	0.937
	38	0.3448	0.3251	0.943
Horizontal translation (Spacing between dowel bars)	250	0.3331	0.3184	0.956
	300	0.3459	0.3241	0.937
	350	0.3375	0.3091	0.916
Vertical translation (Depth of dowel bar)	100	0.3459	0.3241	0.937
	125	0.3025	0.2829	0.935
Longitudinal translation (Dowel bar's embedment length)	178	0.3459	0.3241	0.937
	128	0.3465	0.3186	0.919
Joint opening	2	0.3459	0.3241	0.937
	4	0.346	0.3231	0.934
	6	0.3461	0.3219	0.930
	8	0.3462	0.3207	0.926
	10	0.3463	0.3195	0.923
	12	0.3465	0.3182	0.918
Coefficient of friction	0.05	0.3459	0.3241	0.937
	0.5	0.3458	0.3243	0.937
	1	0.3458	0.3244	0.938

[a] *Deflection at the loaded slab*

[b] *Deflection at the unloaded slab*

[c] *Load transfer efficiency*

Chapter 6

Discussion

This chapter presents the discussions based on a literature survey and numerical studies. The sequential discussions provide answers to the research questions addressed in this thesis.

6.1 Methods to repair concrete pavements

Asphalt overlay is a common method used to rehabilitate concrete pavements. However, due to the continuous movements of the underlying existing concrete pavement, reflective cracking often appears on the asphalt surface at an early stage. These cracks allow water to infiltrate the pavement structure, leading to spalling and corrosion of dowel bars. This technique is time-efficient and cost-effective but may not result in durable pavements.

Rapid-strength concrete is a well-known alternative for quickly rehabilitating distressed pavement and minimizing traffic disruptions. However, the performance of rapid-strength concrete is greatly affected by temperature and moisture gradients, which leads to the built-in curling or warping distortion of the concrete slab. The distortion can cause the slab to rise at the edges or in the middle and as a result, flexural stresses develop in the slab. The effect of curling or warping on premature cracking might be more notable than the traffic load. Consequently, rehabilitation using this technique may not produce long-lasting pavements.

Precast concrete technology is the most suitable alternative for repairing distressed pavement on heavy-traffic-volume roads. This technology efficiently rehabilitates concrete pavements within a short work window, as precast slabs are manufactured in a factory and ready for installation upon arrival at the construction site. The system components, such as epoxy or grouting material, require minimal time to achieve the required strength before opening to traffic. The precast slabs are fabricated in a controlled environment, so the issues related to concrete delivery to the project site are eliminated. Furthermore, proper curing of the slabs eliminates problems like curling or warping. As a result, precast technology incorporates durable concrete and ensures long-lasting performance. The installation of the precast slab is a technical process that might require two or three skilled workers in the crew. Without proper alignment, where the precast slab does not match the base surface or voids are left between the slab and base surfaces, there is a possibility of cracking due to excessive faulting.

6.2 Effectiveness of dowel bar for load transfer

Dowel bars play an important role when connecting a new slab or replacing a slab to the existing pavement, facilitating the transfer of loads between adjacent slabs and minimizing the potential for faulting. In the literature on precast concrete slabs used for concrete pavement repair, various studies have discussed different locations for dowel bars, including the top, bottom or at mid-height of the concrete slab. However, the results from the numerical analysis showed that the proper positioning of the dowel bar, size of the dowel bar, deviation of the dowel bar from its intended position and joint opening evidently affect the load transfer efficiency. Notably, the load transfer efficiency consistently exceeds 0.9, which may be attributed to the base layer's contribution to load transfer due to its high stiffness.

Chapter 7

Conclusions and further research

This chapter presents the conclusions of the work in this thesis and proposes suggestions for future research.

7.1 Conclusions

- The appropriate method for rehabilitating concrete pavement is the precast concrete technology. The literature study showed that this technology can significantly reduce lane closure time as the immediate return to traffic operation is possible. Furthermore, precast slabs provide durable, safe and smooth pavements.
- The study revealed that the optimal load transfer efficiency is attained by positioning the dowel bar at the mid-depth of the concrete slab. In addition, evident differences in load transfer efficiency were observed when evaluating dowel bars at different positions. It was also observed that the mislocation and size of the dowel bar had a manifest impact on the joint efficiency.
- The results demonstrated that increased joint width decreases the dowel bar load transfer efficiency between adjacent slabs.
- The investigation showed that the interaction between concrete slabs is slightly affected by the bond between the concrete slab and the dowel bar.

7.2 Further research

- The free movements of the joints might be significantly affected by the misaligned or skewed dowel bars, potentially leading to joint lockup and concrete cracking around the dowel bars and consequently, the pavement's service life might be compromised. Future research should investigate the impact of a single skewed dowel bar or multiple skewed dowel bars in consecutive or alternative joints.

- Future research should focus on evaluating the performance of in-service concrete pavements with mislocation or misalignment that have been subjected to continuous traffic over time.

- Spalling and joint lockup are crucial concerns in jointed plain concrete pavements. Further research should focus on investigating their causes at transverse joints.

- As mentioned earlier, a field test was initially planned, which unfortunately could not be conducted. Future research should consider the full-scale test to demonstrate the use of precast slabs for the damage repair of highways and evaluate the rehabilitated pavement's structural performance over time under traffic loading.

- Cement production significantly contributes to the global CO_2 emissions in the concrete industry. To address this environmental issue, more research should be devoted to making the concrete pavements more sustainable i.e., by replacing Portland cement with alternative cementitious material such as fly ash or silica fume.

- In Sweden, concrete pavements are typically cast in two layers. The top layer incorporates high-quality aggregates to enhance wear resistance, while the lower layer uses local aggregates. An investigation is needed to determine the feasibility of producing concrete pavements in three layers — top, middle and bottom. The top and bottom layers would use high-strength concrete and the middle layer would utilize moderate strength, which could be achieved by lowering the cement content, thereby potentially reducing CO_2 emissions.

Bibliography

Abut, Y. and Gür, A. (2023), Recent advances in composite pavements in kocaelİ-tÜrkİye, Proceedings, 14th International Symposium on Concrete Roads, Krakow, Poland, June 25-28.

ACI327R-14 (2015), Guide to roller-compacted concrete pavements, American Concrete Pavement Association.

ACPA (1994), Fast-track concrete pavements, Technical report, American Concrete Pavement Association, Skokie, Illinois,, USA.

ACPA (1995), Guidelines for full-depth repair, Technical report, American Concrete Pavement Association, Report No: TB002.02P Skokie, Illinois, USA.

ACPA (1998), Guidelines for partial-depth spall repair, Technical report, American Concrete Pavement Association, Report No: TB003.02P, Skokie, Illinois, USA.

ACPA (2014), Roller-compacted concrete pavements as exposed wearing surface, Technical report, American Concrete Pavement Association.

Bauchkar, S., D. and Chore, Dr, H. S. (2012), 'Roller compacted concrete: A literature review', *IOSR Journal of Mechanical and Civil Engineering* pp. 28–32.

Brunette, B. E. and Lundy, J. R. (1996), 'Use and effects of studded tires on oregon pavements', *Transportation Research Record* **1536**(1), 64–72.

Caltrans (2015), Concrete pavement guide, Technical report, California Department of Transportation.

Ceylan, H., Yang, S., Gopalakrishnan, K., Kim, S., Taylor, P. and Alhasa, A. (2016), Impact of curling and warping on concrete pavements, Technical report, National Concrete Pavement Technology Center - Institute of Transportation, Report No:IHRB Project TR-668, Iowa.

Chang, G. K., Karamihas, S. M., Rasmussen, R. O., Merritt, D. and Swanlund, M. (2008), Quantifying the impact of jointed concrete pavement curling and warping on pavement unevenness, 6th symposium on pavement surface characteristics, Potoroz, Slovenia.

Cotter, A. and T., M. S. (2010), Studded tire wear on portland cement concrete pavement in the washington state department of transportation route network, Technical report, Washington State Transportation Center, Washington, United States.

Delatte, N. (2008), *Concrete Pavement Design, Construction, and Performance*.

Dolk, E. (2017), Concrete pavements' resistance to studded tyres, Proceedings, XVII Nordic Concrete Research Symposium, Aalborg, Denmark.

FHWA (2019), Technical advisory: concrete pavement joints, Technical report, Federal Highway Administration, United States.

Frentress, D. P. and Harrington, D. (2011), Partial-depth repairs for concrete pavements, Technical report, CP Road Map.

Gucunski, N. (1998), Development of a design guide for ultra-thin whitetopping (utw), Technical report, Center for Advanced Infrastructure & Transportation, FHWA 2001 - 018, Rutgers, United States.

Hansen, W. and Wei, Y. (2008), Pcc pavement acceptance criteria for new construction when built-in curling exists, Technical report, Michigan Department of Transportation, Department of Civil and Architectural Engineering, Report No: RC-1481, United States.

Harrington, D., Abdo, F., Adaska, W., Hazaree, C. V. and Ceylan, H. (2010), Guide for roller-compacted concrete pavements, Technical report, National Concrete Pavement Technology Center - Institute of Transportation, Iowa.

Harrington, D., Ayers, M., Cackler, T., Fick, G., Schwartz, D., Smith, K., Snyder, M. B. and Dam, T. V. (2018), Guide for concrete pavement distress assessments and solutions: Identification, causes, prevention and repair, Technical report, National Concrete Pavement Technology Center, Iowa State University, Ames, IA.,.

Hultqvist, B.- and Dolk, E. (2014), Handbok – drift, underhåll och reparation av betongvägar, Technical report, Swedish National Road and Transport Institute (VTI), Linkköping, Sweden.

Khazanovitch, L., Hoegh, K. and Snyder, M. B. (2009), Guidelines for dowel bar alignment in concrete pavement, Technical report, National Cooperative Highway Research Program, Report No:637, Washington, D.C., United States.

Kim, D. H., Suliman, M. R. and Won, M. (2007), Literature review on concrete pavement overlays over existing asphalt pavement structures, Technical report, Center for Transportation Research, Report No: FHWA/TX-08/0-5482-1, United States.

Lawal, A. (2022), 'White topping: A review of design and construction procedures', *International Research Journal of Engineering and Technology (IRJET)* **9**(9), 553–558.

Lytton, R. L. (1989), 'Use of geotextiles for reinforcement and strain relief in asphalt concrete', *Geotextiles and Geomembranes* **8**, 217–237.

Löfsjögård, M. and Karlsson, R. (2004), 'Performance assessment of concrete roads in sweden', *Road Materials and Pavement Design* **5**(2), 193–213.

Mateos, A., Harvey, J., Paniagua, J. C. and Paniagua, F. (2015), Development of improved guidelines and gesigns for thin whitetopping: Literature review, Technical report, California Department of Institution (Caltrans), Report No: CA162878A, United States.

Miller, J. S., Bellinger and Y., W. (2014), Distress identification manual for the long-term pavement performance program, Technical report, Federal Highway Administration, Report No: FHWA-HRT-13-092, McLean, United States.

Plei, M. and Tayabji, S. (2012), Continuously reinforced concrete pavement performance and best practices, Technical report, Federal Highway Administration (FHWA), Report No. FHWA-HIF-12-039, United States.

Rao, C., Barenberg, E. and Snyder, M. B. (2001), Effects of temperature and moisture on the response of jointed concrete pavements, Proceedings, 7th International Conference on Concrete Pavements, Orlando, Florida.

Rasmussen, R. O. and Rozycki, D. K. (2004), *Thin and Ultra-Thin Whitetopping: A Synthesis of highway practice*, Vol. 338, Transportation Research Board, Washington, D.C., United States.

Roesler, J. R., Hiller, J. E. and Brand, A. S. (2016), Continuously reinforced concrete pavement manual - guidline for deign, construction, maintenance, and rehabilitation, Technical report, Federal Highway Administration (FHWA), Report No. FHWA-HIF-16-026, United States.

Selvam, M., Kumar, M. N. and Singh, S. (2023), 'Comparative analysis of jointed plain concrete pavement and roller-compacted concrete pavement', *Transportation Research Record* pp. 1–15. https://doi.org/10.1177/03611981231188722.

Shahin, D. M. Y. (2009), Concrete surfaced airfield s- paver™ distress identification manual, Technical report, US ARMY CORPS OF ENGINEERS, United States.

Shoenberger, J. E. (1994), *User's guide: roller-compacted concrete pavement*, US Army Center for Public Works, Alexandria.

Silfwerbrand, J. (1995), Dimensionering av betong-beläggningar, Technical report, KTH Royal Institute of Technology, Dept of Structural Mechanics and Engineering, Report No. 9, Stockholm, Sweden (In Swedish).

Silfwerbrand, J. (2014), The advantages of concrete pavements in tunnels, Proceedings, 12th International Symposium on Concrete Roads, Prague, Sept. 24-26.

Silfwerbrand, J. (2016), Not concrete or asphalt but concrete and asphalt – a discussion based on swedish pavements, Proceedings, 11th International Conference on Concrete Pavements, San Antonio, Texas, USA, August 28-31.

Silfwerbrand, J. (2023), Concrete pavements for modern swedish highways, Proceedings, 14th International Symposium on Concrete Roads, Krakow, Poland, 25-28 June.

Smith, P. and Snyder, M. B. (2019), Manual for jointed precast concrete pavement], Technical report, National Precast Concrete Association, United States.

Strömberg, L., Silfwerbrand, J., Ansell, A. and Hintze, S. (2020), 'Making concrete pavements competitive by using the standardized framework for comparisons of infrastructure projects in terms of cost-efficiency and climate impact', *Nordic Concrete Research* **62**(1), 21–39.

Syed, M. A. (2021), Design and implementaion of prestressed precast concrete pavement (doctoral dissertation), Technical report, Visvesvaraya National Institute of Technology, Department of Applied Mechanics, Nagpur,India.

Tayabji, S. and Plei, M. (2019), Optimized design details for continuously reinforced concrete pavements:[techbrief], Technical report, Federal Highway Administration (FHWA), Report No. FHWA-HIF-19-066, United States.

Zhang, Q. and Khattak, Mohammad J.and Das, A. (2019), Mitigating reflective cracking through the use of a ductile concrete interlayer, Technical report, Transportation Consortium of South-Central States, Louisiana State, United States.

Zollinger, D. (2016), Roller-compacted concrete pavement:[techbrief], Technical report, Federal Highway Administration (FHWA), Report No. FHWA-HIF-16-003, United States.

Zubeck, H., Aleshier, L., Harvey, S., Porhola, S. and Eric, L. (2004), Socio-economic effects of stdded tire use in alaska, Technical report, University of Alaska Anchorage School of Engineering, Alaska, United States.