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Performance evaluation and construction design of concrete overlays

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Performance evaluation and construction design of concrete overlays

by

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DEDICATION

This dissertation is dedicated to my parents, who have always given me selfless love, and to my wife, who has fully supported me in every area of my life.

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ABSTRACT

Concrete overlays extend the service life of existing pavement and are potentially one of the most cost-effective maintenance and rehabilitation strategies for pavement systems. While concrete overlays are not new, the long-term performance of various types of concrete overlays has not been fully investigated because there has been insufficient performance data available to support such evaluation. The Iowa Pavement Management Program (IPMP), the Iowa Concrete Paving Association (ICPA), and other agencies have created a complete concrete overlays historical performance database, and this historical performance database includes the Pavement Condition Index (PCI), the International Roughness Index (IRI), overlay type, construction year, overlay thickness, joint spacing, traffic, and other construction and design-related data over a 30-year period. This study included more than 300 overlay projects based on more than 1,400 miles of roadway to evaluate the long-term performance of concrete overlays.

The main purpose of this study is to evaluate the long-term performance trend concrete overlays. The effects of overlay type and design features (thickness and joint spacing) on long-term performance were also identified. The effects of structural design alternatives on concrete overlay performance have been identified using the latest version of AASHTOWare Pavement ME Design (Version 2.3.1). Furthermore, to develop and practical ANN model for predicting concrete overlay performance based on historical performance database. In addition, investigating differences in behavior between shorter joint spacing and conventional joint spacing for optimize concrete overlays joint spacing size.

Long-term performance trends can be evaluated by studying PCI and IRI (two measures representative of pavement performance) changes during pavement service life. Performance data dating back to 1998 for all in-service Iowa concrete overlays constructed over the last 38

years were collected and evaluated. To date, since concrete overlays do not reflect new technology, and concrete overlay design procedures still follow empirical methods, this study applied both mechanistic-empirical design software and machine-learning techniques (i.e. AASHTOWare Pavement ME Design (Version 2.3.1) and Artificial Neural Networks (ANN) model) to identify the effects of various design parameters and help in predicting concrete overlay service life. AASHTOWare Pavement ME Design (Version 2.3.1) is a powerful software package able to simulate alternative joint spacing design options on various types of concrete overlays, and it provides theoretical insights for developing recommendations for pavement design. An ANN model is a machine learning tool that has been successfully used in the field of pavement design and analysis. Compared with other statistical techniques, since the deterioration of pavement performance is a non-linear function, the ANN model has shown superior accuracy for pavement management systems. Four different groups (distress data, construction design data, traffic data, and climate data) of input variables were used to predict pavement performance in the ANN model. Non-destructive testing (NDT) is another method for identifying the effects of various design parameters in concrete overlay systems. In this study, ultrasonic low-frequency tomography (MIRA) proved effective in detecting whether a saw-cut was activated. By comparing joint activation results with slab length values and radius of relative stiffness ratio (L/ℓ), recommendations on joint spacing for Iowa concrete overlays were developed.

Results from a summary of long-term performance showed that concrete overlays can extend service life of existing pavement by at least 20 years. After a comprehensive review of concrete overlay performance data, the adequate and substandard performance data were identified, showing differences between adequate and substandard performance over a 10-year service life, and indicating that improving construction quality to eliminate premature failure can also increase concrete overlay service life. In additional, compared to historical performance-related data, the Pavement ME Design software results is conservative in predicting concrete overlay service life. On the other hands, according to the concrete overlays prediction models results, the ANN model resulted in a root mean squared error (RMSE) of less than 10% of the range of IRI values, indicating that the ANN model was successful in predicting Iowa concrete overlay performance. Compared with MIRA evaluate rates of joint activation results and slab length values and radius of relative stiffness ratio (L/ℓ), joint spacing should be based on L/ℓ value between 4 and 7.

CHAPTER 1. INTRODUCTION

1.1 Background

Since pavement repair and rehabilitation have become necessary nationwide, strategies for increasing the remaining service life of the rigid or flexible pavements to extend pavement life must be considered, and the most common recommendation is use of an overlay pavement (Bagate, McCullough, & Fowler, 1987). Concrete overlays provide several advantages (Harrington & Fick, 2014):

- Cost-effective maintenance and rehabilitation strategies for extending pavement service life.
- Compared with conventional concrete pavement concrete, overlays can be rapidly constructed.
- Because of their small thickness and lack of reinforcement, concrete overlays are easy to repair.

There have been many government agencies interested in using concrete overlays. Iowa is one of the states using concrete overlay since the 1970s, and up to now there have been more than 500 projects, with more than 2,000 miles of concrete overlay pavements regularly constructed on Iowa roadways. While concrete overlays are not a new type of pavement system, and 46 states have successfully constructed them, there is a lack of studies investigating long-term performance of all types of concrete overlays. This dissertation will provide comprehensive information with respect to concrete overlay construction design, including selection of overlay type, optimized joint spacing and overlay thickness. Iowa concrete overlay performance data have been obtained from a pavement distress data set maintained by the Iowa pavement management program (IPMP). This collection of concrete overlay pavement performance data included transverse cracking, longitudinal cracking, faulting, D-cracking, joint spalling, patching, and international roughness index (IRI). Using these data, a pavement condition index (PCI) was calculated for each concrete overlay project of the IPMP.

Concrete overlays can provide an additional 15 to 40 years of service life to both low and high volume roads. Concrete overlay types include bonded concrete-on-concrete (BCOC), unbonded concrete-on-concrete (UBCOC), bonded concrete-on-asphalt (BCOA), and unbonded concrete-on-asphalt (UBCOA). Both BCOC and UBCOC existing pavement is old concrete pavement; BCOC thickness can vary from 51 mm. (2 in.) to 152 mm. (6 in.) and overlay joints must match joints in the underlying pavement. UBCOC thickness are between 102 mm. (4 in.) and 279 mm. (11 in.), and an interlayer should provide separation from the underlying pavement. Historically BCOA and UBCOA are referred to as whitetopping in which existing pavement is old asphalt pavement; for BCOA slab thickness was less than or equal to 152 mm (6 in.), while for UBCOA slab thickness was greater than 152-mm (6 in.) (Gross et al., 2017).

In recent years, concrete overlays have become popular for use in extending pavement service life. This dissertation uses a database of Iowa 384 concrete overlay projects and mechanistic-empirical design software (AASHTOWare Pavement ME Design (Version 2.3.1)) to evaluate concrete overlay long-term performance, and to indicate which design parameters (i.e. overlay types, thickness, and joint spacing) influence concrete overlay performance. This dissertation also uses artificial neural networks (ANN) to predict performance of concrete overlay ride quality (i.e., International Roughness Index (IRI)). In addition, 54 concrete overlay projects have been studied using an ultrasonic shear-wave tomography (MIRA) device for joint activation analysis. Joint activation evaluation of concrete overlays is one of the important parameters for optimizing joint spacing.

1.2 Objective

Because recent studies of concrete overlay performance encompassed only a limited number of projects or investigated only one type of concrete overlay, the main objective of this study is to determine the performance of concrete overlays and identify the effects of overlay type and design features on long-term performance. To accomplish this main purpose, the following objectives have been established:

- To develop a comprehensive concrete overlay performance data dating back to 1998 for all in-service Iowa concrete overlays constructed over the last 38 years.
- To investigate concrete overlay performance data and to identify occurrences of both adequate and substandard performance.
- To identify the effects of structural design alternatives on concrete overlay performance using the latest version of AASHTOWare Pavement ME Design (Version 2.3.1).
- To provide theoretical insights and assist in developing recommendations with respect to optimized joint spacing and overlay thickness.
- To develop a valuable and practical ANN model of predicting concrete overlay performance based on field data collection.
- To investigate differences in behavior and impact between shorter (i.e. 1.83 m. (6 ft.)) joint spacing and conventional (i.e. more than 3.66 m. (12 ft.)) joint spacing for concrete overlays.

1.3 Significance of Research

This dissertation's concrete overlay database is comprised of a large, comprehensive data set containing all concrete overlay types and representing many more years of performance than found in existing literature, where analysis of concrete overlay performance has often been limited in scope to a particular type of overlay or a small set of projects. This study of concrete overlay trends shows that performance varies based on different types of overlay, PCC slab thickness, and panel size. The significance of this study is as follows:

- Successful evaluation of concrete overlay long-term performance trends and completion of the first major concrete overlay performance study.
- Successful use of historical data for comparison with results for Pavement ME and BCOA ME to identify the effects of design parameters on concrete overlay service life.
- Successful developed ANN model to predict Iowa concrete overlay performance based on this comprehensive data set.
- Successful utilization of MIRA device results comparing slab length and radius of relative stiffness ratio (L/ℓ) for recommending optimal panel size.

1.4 Dissertation Organization

This dissertation is a combined journal paper and report separated into seven chapters. Chapter 1 provides general background, objectives, significance of research and dissertation organization.

Chapter 2 provides a brief literature review of concrete overlay systems and analytical methods, including types of overlays and concrete overlay design procedures. The concrete overlay analytical methods include performance prediction model development, and joint factors.

Chapter 3 presents the first journal paper: Long-term Performance Evaluation of Iowa Concrete Overlays that discusses evaluation of PCI and IRI (two measures representative of pavement performance) changes during service life and the effects of overlay type and design features (including overlay thickness and joint spacing) on long-term performance of Iowa concrete overlays.

Chapter 4 presents the second journal paper: Effect of Joint Spacing and Pavement Thickness on Concrete Overlay Performance, with a review of PCI data indicating that improving construction quality to eliminate premature failure has the potential to add at least 10 years to the service life of PCC overlays. It also describes use of AASHTOWare Pavement ME Design (Version 2.3.1) software to identify the effects of design parameters on concrete overlay service life.

Chapter 5 presents the third journal paper: Iowa Concrete Overlay Performance Prediction Using Artificial Neural Networks: An Evaluation. This journal paper discusses using entire Iowa concrete overlay performance data to generate a realistic prediction model. This accurate prediction model provides decision makers with optimal strategies to extend pavement service life.

Chapter 6 presents the fourth journal paper: Evaluation Joint Activation and Optimization Concrete Overlays Joint Spacing discusses pavement joints as primary means for controlling cracks in concrete slabs and helping to release stresses. Since cracks not occurring below saw-cut joints reflects joints that are too sparse, using non-destructive testing (NDT) to determine the joint activation can produce results for optimizing concrete overlay joint spacing.

Chapter 7 summarizes the art contributions to engineering research and practice, the research major findings of this dissertation and provides recommendations for future research.

1.5 References

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Gross, J., King, D., Harrington, D., Ceylan, H., Chen, Y.-A., Kim, S., Taylor, P., and Kaya, O. (2017). *Concrete Overlay Performance on Iowa's Roadways* (No. IHRB Project TR-698) (p. 149). Ames, IA: National Concrete Pavement Technology Center, Iowa State University. Retrieved from http://www.intrans.iastate.edu/research/documents/research-reports/Iowa_concrete_overlay_performance_w_cvr.pdf

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CHAPTER 2. LITERATURE REVIEW

2.1 Review on Concrete Overlays System

Use of concrete overlays is a rehabilitation and preservation strategy for extending pavement service life (Delatte, 2001). Since concrete overlays provide a relatively cost-effective technique compared, and their use can provide an additional 15 to 40 years of service life for both low and high volume roads, they have been selected by many countries as well as by many states in the United States. Iowa is one such state with considerable interest in concrete overlays and it has a long history of concrete overlay road projects. There are two major groups of concrete overlays, bonded concrete overlays and unbonded concrete overlays. In general, bonded concrete overlays are used to address surface distress when the existing underlying pavement is in good or fair condition, while unbonded concrete overlays are used to rehabilitate pavements with some structural deterioration (Torres, Roesler, Rasmussen, & Harrington, 2012). Although previous studies define six different types of concrete overlays, the database used did not distinguish between asphalt pavements and composite pavements (Gross et al. 2017), so four concrete overlay types are included in this study (see Figure 2-1): bonded concrete on concrete (BCOC), unbonded concrete on concrete (UBCOC), bonded concrete on asphalt (BCOA), and unbonded concrete on asphalt (UBCOA).

There are many important factors influencing concrete overlay performance, including slab thickness, joint spacing size, concrete material properties, and drainage system (King and Roesler 2014), and existing pavement condition is another important issue affecting concrete overlay performance, with thickness and condition of existing asphalt pavement especially critical in affecting BOCA and UBCOA service life (Mateos, Harvey, Paniagua, Paniagua, & Center, 2015; J. Vandenbossche, Barman, Mu, & Gatti, 2011). Moreover, pavement distresses of concrete overlays include material-related distresses (MRD) such as alkali-silica reaction (ASR), D-cracking, and freeze-thaw damage (Harrington & Fick, 2014), as well as load-related distress that include transverse cracking, faulting, and joint spalling (Otto Rasmussen, McCullough, Ruiz, Mack, & Sherwood, 2002). To mitigate such distresses, achieve good performance, and extend service life and performance, concrete overlays should be properly designed and constructed, considering concrete overlay type, concrete mix design, concrete overlay thickness, joint spacing, and many other construction-related variables.

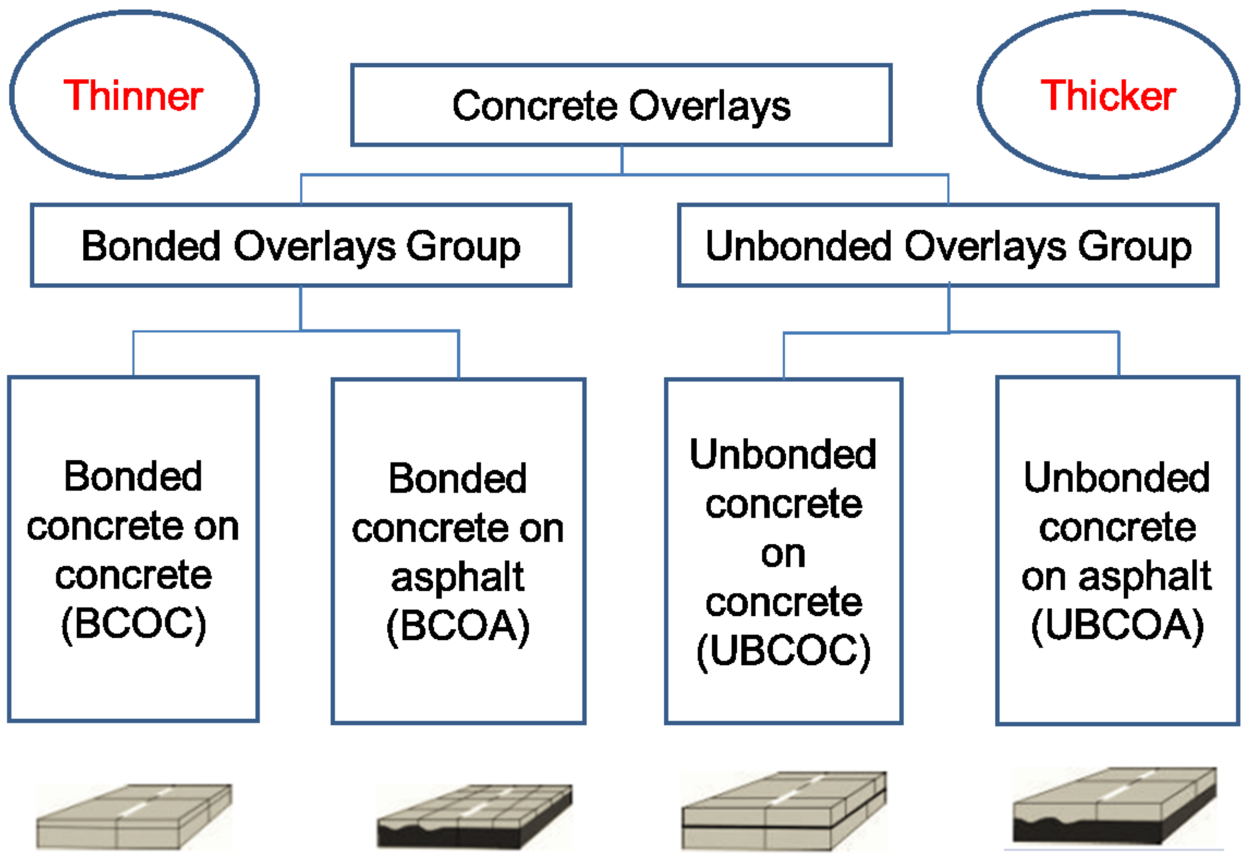


Figure 2-1 *Concrete overlay categories (redrawn from Harrington, 2009)*

2.1.1. Bonded Concrete on Concrete (BCOC)

BCOCs use paving over existing concrete pavement, with the purpose of increasing existing pavement structural capacity and eliminating surface distress, so the existing pavement should be in good condition as shown in Figure 2-2. Advantages of BCOCs include cost effectiveness, improved pavement service life, and reduced road-closure time during construction (Delatte Jr, Fowler, McCullough, & Gräter, 1998), although adequate bonding must be achieved and maintained to realize these benefits.

BCOCs typically range in thickness from 51mm. (2 in.) to 152mm. (6 in.) (Torres et al., 2012). BCOC joints have to be placed to match those in the existing pavement to prevent reflective cracking (Khazanovich & Gotlif, 2003). Also, since BCOC cannot prevent joint deterioration, especially D-cracking, the time interval between design and construction of BCOC is important (McCullough & Fowler, 1994). Most bonded overlay projects are therefore more challenging than unbonded overlay projects since bond quality is especially important to performance of concrete overlay. A good bond makes a new concrete overlay and existing pavement into one pavement.

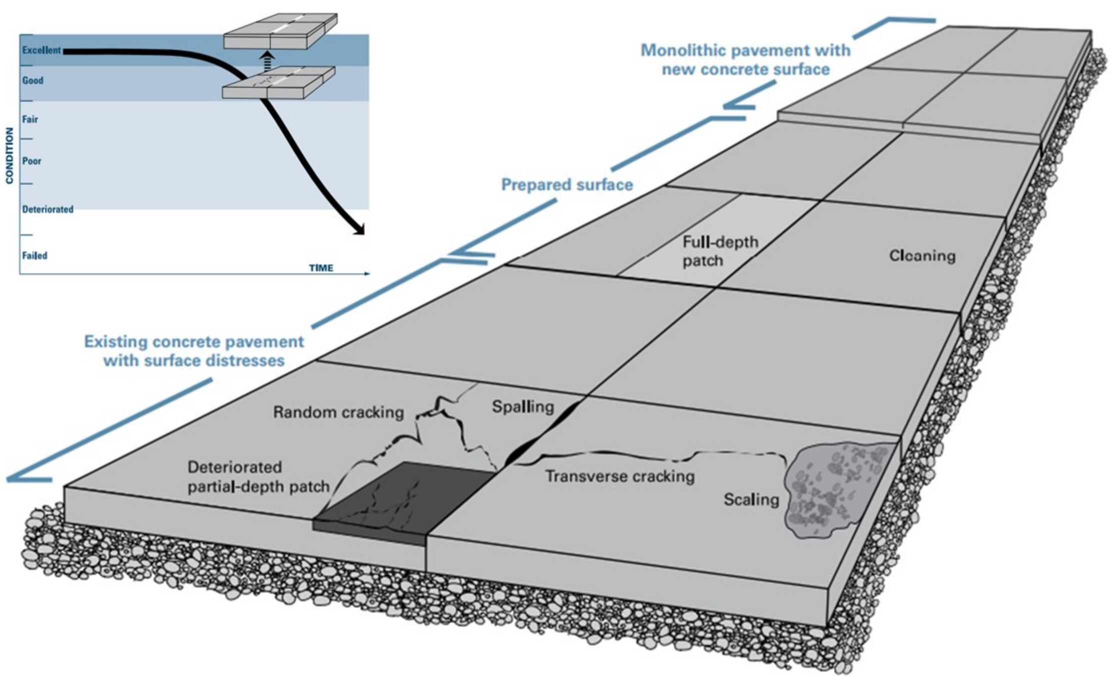


Figure 2-2 *BCOC of good condition concrete pavement with surface distresses (Harrington et al. 2014)*

2.1.2. Unbonded Concrete on Concrete (UBCOC)

Since UBCOCs are constructed with a debonding layer placed over the existing concrete pavement, they require a thin separation interlayer between overlay and existing pavement. This interlayer, typically constructed using HMA or geotextile, has the purpose of preventing reflective cracking by allowing concrete overlay and existing pavement to move differentially (Torres et al., 2012). The main benefit of UBCOCs are that they can control distresses of existing pavement, improve structural capacity, and existing pavement could be in fair to poor condition, as shown in Figure 2-3.

UBCOCs typical thicknesses are 102-mm. (4 in.) to 279-mm. (11 in.) (Torres et al., 2012). Unbonded concrete overlays are typically thicker than bonded concrete overlays because the new layer must be structurally independent of the lower layer. Since UBCOCs are usually designed as new concrete pavement, they can be constructed using any type of concrete (i.e. JPCP or CRCP).

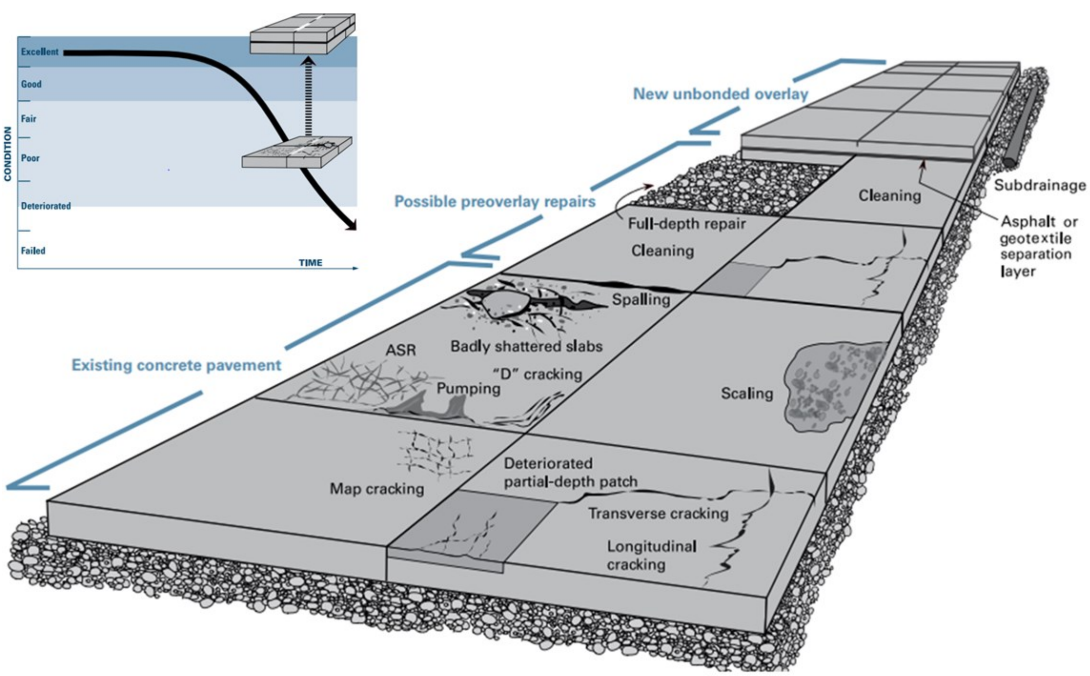


Figure 2-3 *UBCOC of poor condition concrete pavement with surface distresses (Harrington et al. 2014)*

2.1.3. Bonded Concrete on Asphalt (BCOA)

BCOAs are paved over existing asphalt pavement, and historically a BCOA was described as whitetopping. To date, concrete overlays on asphalt with slab thicknesses less than or equal to 152mm (6 in.) were designated as BCOA (Gross et al. 2017). BCOA is a popular rehabilitation and preservation option for repairing existing asphalt pavement. In general, BCOA designs are recommended to use short or medium panel size (i.e., 1.52 m. × 1.52 m. (5 ft. × 5 ft.), 1.83 m. × 1.83 m. (6 ft. × 6 ft.) and 2.44 m. × 2.44 m. (8 ft. × 8 ft.)) because of low thickness, curling stress, and desire to keep wheel path out of longitudinal joints (Alland, Vandenbossche, DeSantis, Snyder, & Khazanovich, 2018; Titus-Glover, Bhattacharya, Raghunathan, Mallela, & Lytton, 2016). The main purpose of BCOA is to increase structural capacity and eliminate existing pavement distress.

Since existing asphalt pavement distresses are easily reflected into new concrete overlays, existing pavement condition is one of the most critical factors contributing to long-term BCOA performance, so the existing pavement should be in good condition as shown in Figure 2-4. Thus, good surface preparation (i.e. milling, surface cleaning, and misting) is significant before BCOA construction (J. M. Vandenbossche & Sachs, 2013). Milling the existing asphalt pavement could eliminate surface distresses, cleaning the existing pavement surface could ensure proper bonding, and misting the original pavement surface could decrease the potential for shrinkage cracking while also decreasing the asphalt surface temperature (Mateos, Harvey, Paniagua, Paniagua, et al. 2015).

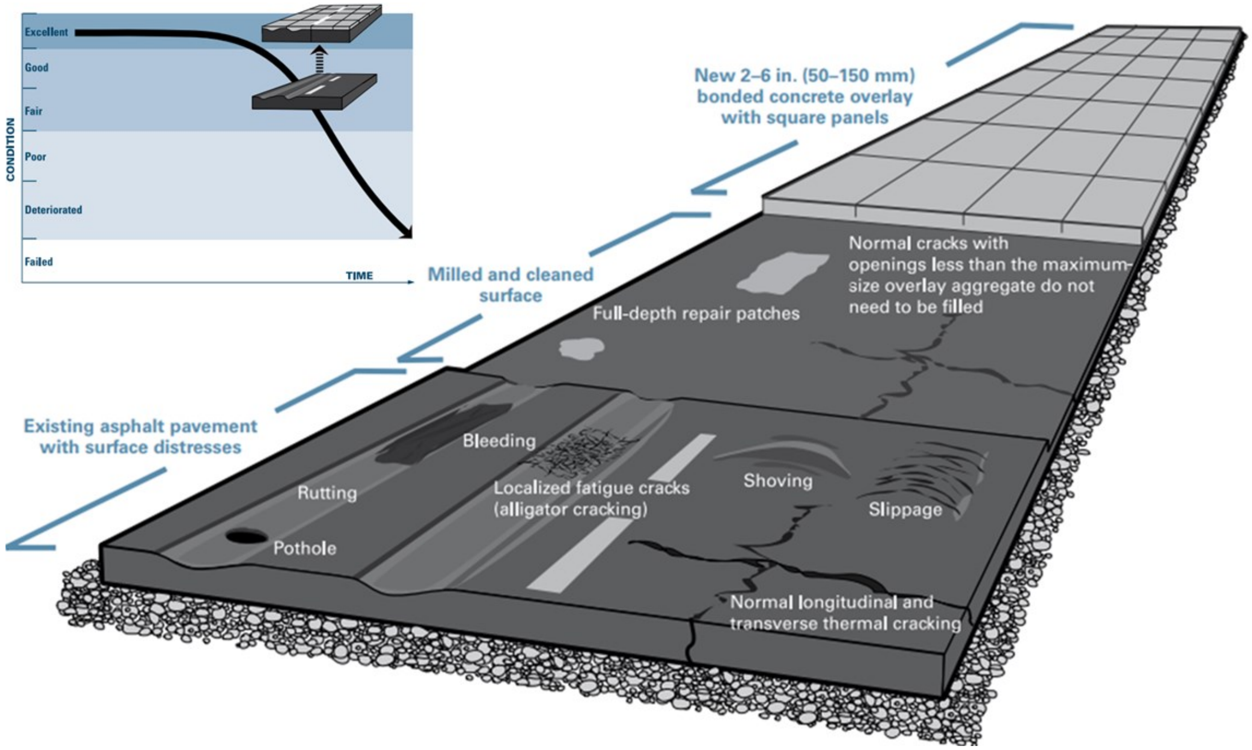


Figure 2-4 *BCOA of good or fair condition concrete pavement with surface distresses (Harrington et al. 2014)*

2.1.4. Unbonded Concrete on Asphalt (UBCOA)

UBCOAs are paving over existing asphalt pavement, also historically described as whitetopping. To date, concrete overlays on asphalt with slab thicknesses greater than 152 mm (6 in.) were designated as UBCOA (Gross et al. 2017). In contrast to BCOA and UBCOA, UBCOAs are designed as new conventional concrete pavement, so they are more appropriate for repairing significantly-deteriorated existing asphalt pavement. Milling of existing asphalt pavement is also required to reduce or eliminate such significant deterioration.

Since the benefit of UBCOA is the requirement for only minimal existing pavement surface preparation, and this type of concrete overlay could be constructed on asphalt pavement in poor condition, as shown in Figure 2-5., major repairs in existing pavement are not required.

Although UBCOA are not bonded overlays, partial bonding between new concrete overlays and existing asphalt pavement could improve overlay performance (Harrington & Fick, 2014).

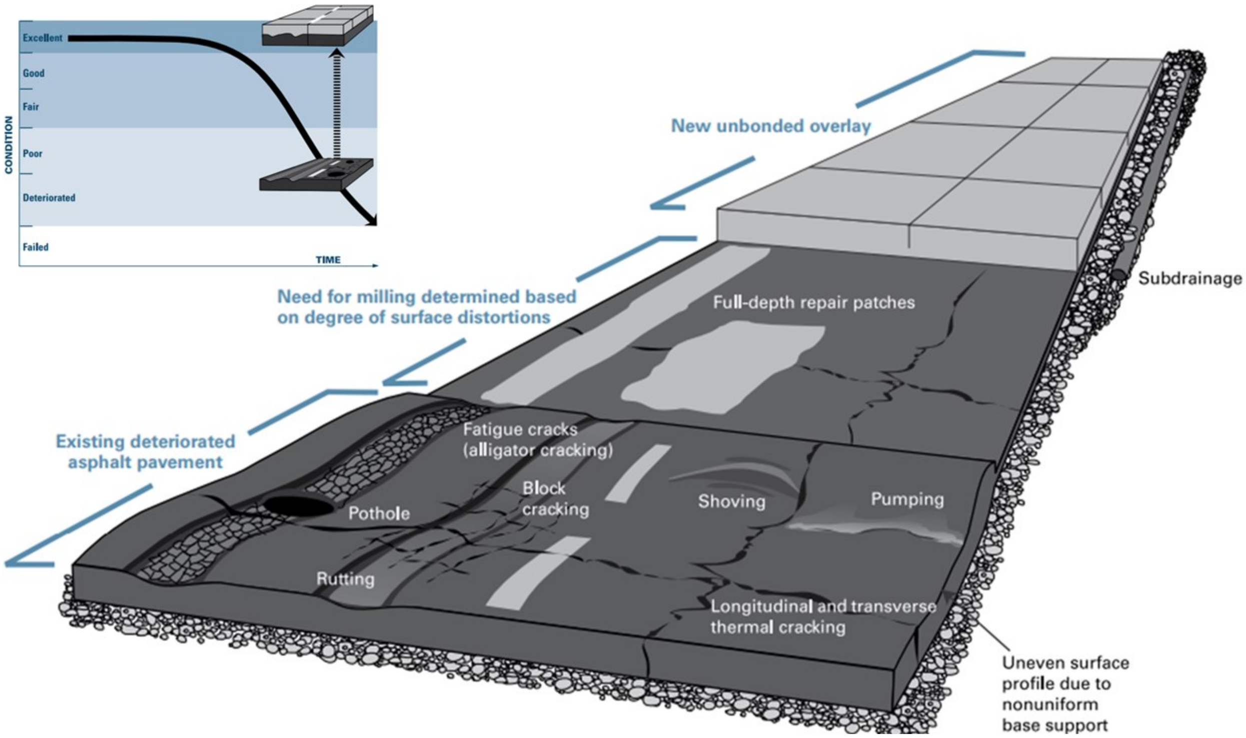


Figure 2-5 *UBCOA of poor condition concrete pavement with surface distresses (Harrington et al. 2014)*

2.2 Concrete Overlays Analytical Method

2.2.1. Iowa Concrete Overlay Historical Data Analysis

Concrete overlay performance data were obtained from pavement distress databases maintained by the Iowa Pavement Management Program (IPMP). An IPMP vendor using an automatic road analyzer (ARAN) has collected data on state and local highways since 1998. The pavement distress data includes transverse cracking, longitudinal cracking, faulting, D-cracking, joint spalling, and International Roughness Index (IRI), among others. Using these pavement condition data, the IPMP calculated the PCI for each concrete overlay project using Equation 2-1 (Gross et al. 2017).

$$PCI = 100 - 35\left(\frac{IRI}{253}\right) - 25\left(\frac{\#\ of\ D\text{-}crack\ joints\ per\ 528\ ft}{8}\right) - 15\left(\frac{\#\ of\ spalled\ joints\ per\ 528\ ft}{9}\right) - 25\left(\frac{\#\ of\ transverse\ cracks\ per\ 528\ ft}{14}\right)$$ (Equation 2-1)

The PCI values reflect a widely-accepted method used to represent pavement performance. As shown in

Figure 2-6, PCI values range from 0 to 100.

Figure 2-6 *IPMP PCI rating scale*

According to a FHWA threshold, an IRI value of 2.7 m/km (170 in/mile) is recommended as an acceptable performance threshold, while IRI values higher than 2.7 m/km (170 in/mile) represent unacceptable performance (Arhin, Noel, & Ribbiso, 2015).

2.2.2. Mechanistic-Empirical Design Software

Concrete overlay technology is not new, so many different design methodologies can be used to identify concrete overlay structures, including BCOA-ME (Vandenbossche 2013), Guide for Design of Pavement Structures (AASHTO 1993), StreetPave (ACPA 2012), and AASHTOWare Pavement ME Design (Version 2.3.1) (Torres et al., 2012). To achieve long-lasting concrete overlay performance through proper design and construction practices, it is critical to understand actual concrete pavement performance behavior and identify design and construction-related factors that can result in either substandard or adequate performance of Iowa concrete overlay types. To address such questions, this dissertation uses Iowa concrete overlay historical performance data and two different Mechanistic-Empirical Design Software packages, AASHTOWare Pavement ME Design (Version 2.3.1) and BCOA-ME software, to evaluate the performance of concrete overlays constructed in Iowa.

Both AASHTOWare Pavement ME Design (Version 2.3.1) and BCOA-ME analytical investigation can: (1) simulate alternative joint spacing design options under various conditions (i.e., different traffic loadings, overlay thicknesses, support systems, and overlay types with and without fibers) in situations where field investigation has limitations and (2) provide theoretical insights to developing recommendations for optimized joint spacing along with field investigation results.

AASHTOWare Pavement ME Design (Version 2.3.1) has implemented a concrete overlay design tool (BCOA-ME) developed at the University of Pittsburgh (Bhattacharya, Gotlif, & Darter, 2017) to predict concrete overlay performance and identify concrete overlay structural design alternatives for rehabilitation of existing pavement structures, as shown in Figure 2-7. The effects of the various structural design alternatives on concrete overlay performance have been identified through analytical investigations to provide theoretical insights and assist in developing recommendations with respect to optimized joint spacing and overlay thickness.

Jointed plain concrete pavements (JPCP) in Iowa DOT are assumed to have been designed on average to perform to a selected design criteria at the 50% reliability. If the predicted IRI is higher than 2.7 m/km (170 in/mile), the concrete overlay type analyzed is considered to be in poor condition (Arhin et al., 2015). The AASHTOWare Pavement ME Design IRI prediction model for designing JPCP and concrete overlays includes transverse cracking, joint faulting, joint spalling, and a site factor, along with calibration coefficients, as follows:

$$IRI = IRIini + C1 \times CRK + C2 \times SPALL + C3 \times TFAULT \times 5280/JSP + C4 \times SF \qquad \text{(Equation 2-2)}$$

Where IRI = Predicted IRI; IRI_{ini} = Initial smoothness measured as IRI; CRK = Percent slabs with transverse cracks (all severities); SPALL = Percentage of joints with spalling (medium and high severities); TFAULT = Total joint faulting cumulated; SF = Site factor; JSP = Joint spacing; C 1, 2, 3, 4 = Calibration coefficients

The Pavement ME Design local calibration studies (Ceylan, Kim, Gopalakrishnan, & Ma, 2013; Kaya, 2015) previously conducted for Iowa pavement system cover new jointed plain concrete pavements (JPCP) as rigid pavements, new hot-mix asphalt pavements as flexible pavement, and HMA over JPCPs as composite pavements. In addition, while the Pavement ME design short-jointed plain concrete pavement (SJPCP) module reflects local calibration studies in Minnesota, Missouri, New York, Illinois, Texas, and Colorado mid-size concrete overlays (Alland et al., 2018; Li, Dufalla, Mu, & Vandenbossche, 2016). However, no local calibration study on Iowa concrete overlay systems (bonded or unbonded concrete overlays) has been conducted.

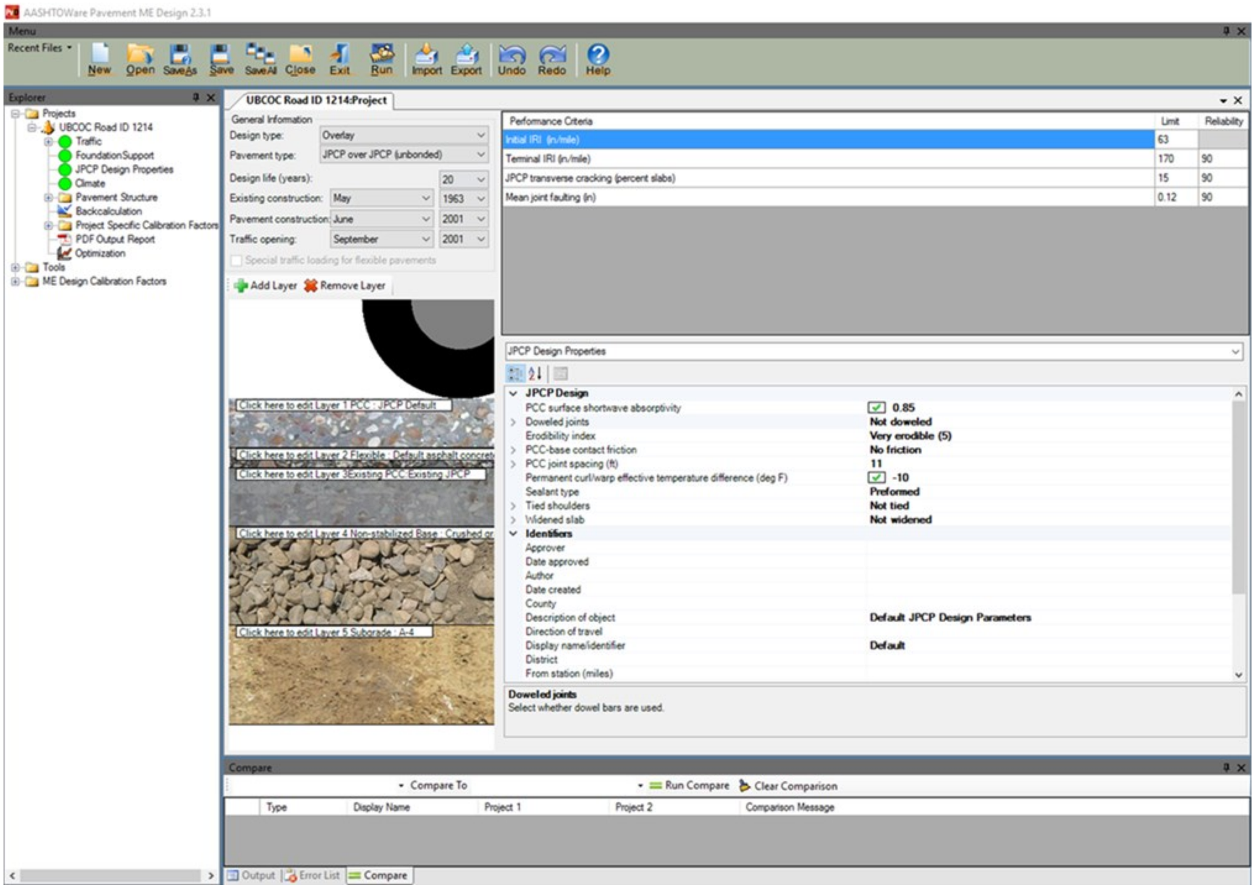


Figure 2-7 *AASHTOWare Pavement ME Design (Version 2.3.1) screen capture*

A bonded-concrete asphalt mechanistic-empirical overlay design procedure (BCOA-ME) has been developed at the University of Pittsburgh (Li et al., 2016), and this software has been used for designing the thin and ultra-thin whitetopping structures shown in Figure 2-8. Unlike Pavement ME Design software, BCOA-ME does not model predicted overlay performance, but provides an overlay thickness after a design parameter has been entered into the BCOA-ME website. Compared with Pavement ME Design software and BCOA-ME design software, BCOA-ME provides input design parameters for fiber type and content. Therefore, to help analyze and compare the predicted performance of different joint-spacing design parameters in BCOA-ME, design thickness was calculated for different variables and plotted as a function of maximum allowable percent slabs cracked.

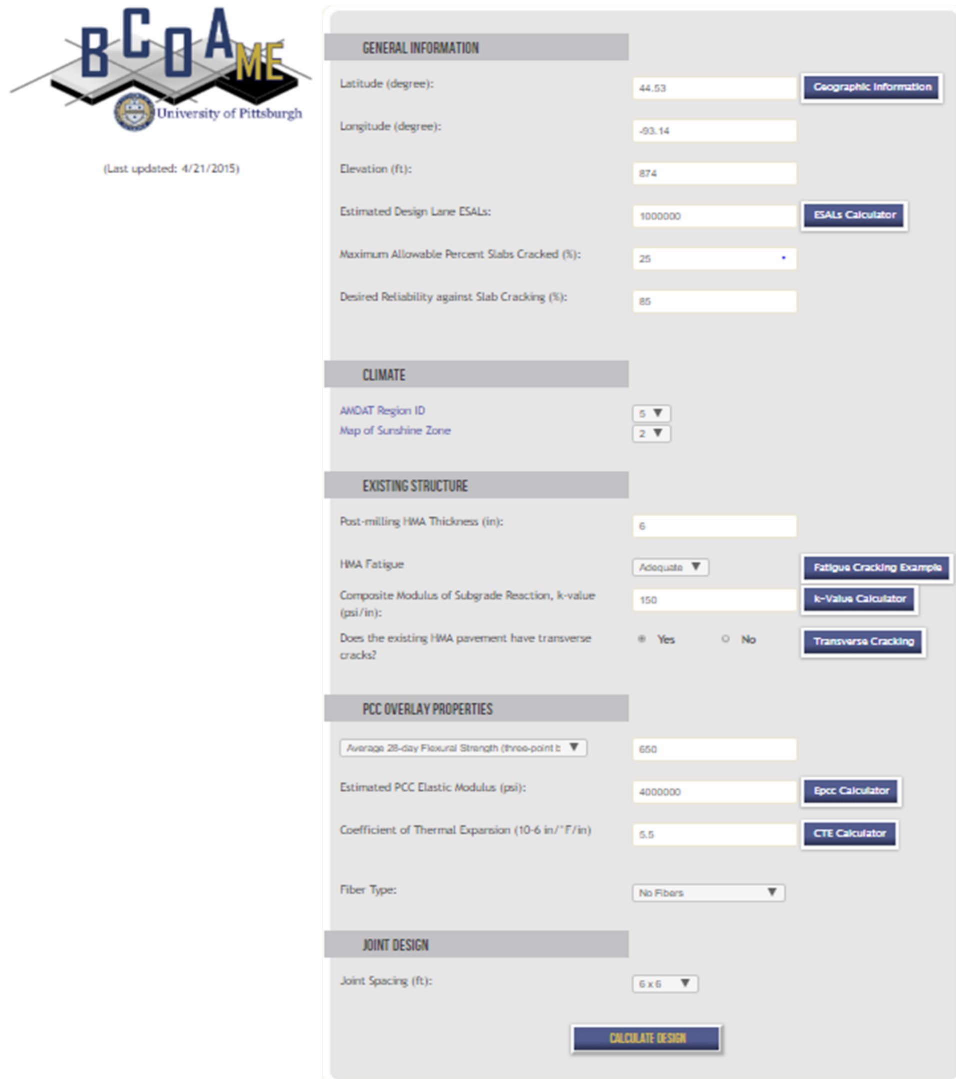


Figure 2-8 *BCOA-ME web screen capture*

2.2.3. Artificial Neural Networks Prediction Software

Pavement condition will deteriorate with pavement age, so prediction of future pavement performance of a road network is important for pavement management systems (PMS). Predicted performance could lead to use of the most cost-effective rehabilitation and maintenance strategy to extend pavement service life (Roberts & Attoh-Okine, 1998; Terzi, 2007). An appropriate pavement performance prediction model can also be used to reduce data-collection and life-cycle costs and contribute to budget optimization (Roberts & Attoh-Okine, 1998). Success of a pavement performance prediction model depends significantly on parameters such as condition data, local traffic, and environmental conditions data.

There are many different types of machine-learning systems that can be used to develop pavement performance prediction models, including Markovian, statistical regression, random forest, and Artificial Neural Networks (ANN) (Abaza, Ashur, & Al-Khatib, 2004). Since they can be automated to learn from data, machine-learning systems exhibit higher accuracy in predicting future pavement performance than traditional statistical techniques. Since artificial neural networks (ANN) are one type of machine learning tool that has produced higher-accuracy results and better understanding of non-linear function (Gardner & Dorling, 1998), they have been successfully used in various types of field applications, particularly in pavement design and analysis and in solving pavement engineering problems (Ceylan, Bayrak, & Gopalakrishnan, 2014; Kaya et al., 2018; Rezaei-Tarahomi et al., 2017). To date, there has been a great deal of literature related to ANN use in successfully-developed concrete material properties and pavement performance prediction models (Butt, Shahin, Feighan, & Carpenter, 1987; Panas, Pantouvakis, & Lambropoulos, 2012).

ANN models represent new advances in artificial intelligence (AI), with such models solving complex problems rapidly (van Gerven & Bohte, 2018). As shown in Figure 2-9, a central property of an ANN model is computing the weight and connection strength of each input parameter and then producing one output result (van Gerven & Bohte, 2018). The main strength of an ANN model is that it can learn and memorize from input parameters, then compare the predicted outputs with original outputs, ultimately generating a realistic prediction model (van Gerven, 2017).

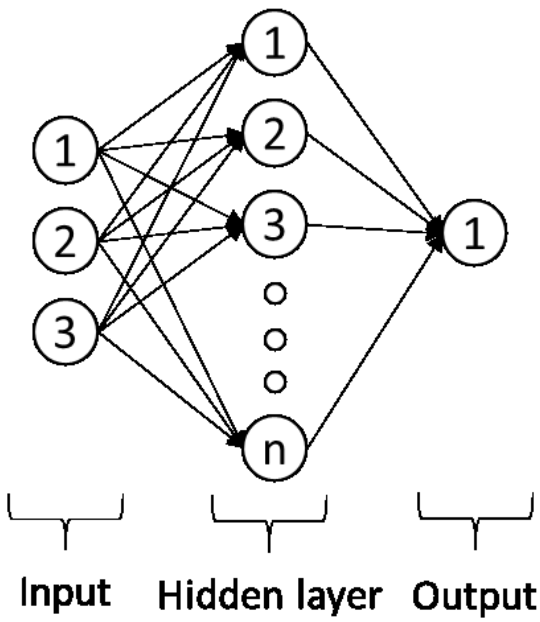


Figure 2-9 *Typical ANN network architecture*

Backpropagation is one of the most widely use algorithms in ANN modelling, and since this type of algorithm can solve many learning problems with training efficiency and noise elimination, it is commonly used to train deep and wide architectures (Marblestone, Wayne, & Kording, 2016). Backpropagation calculates the error between prediction output and observed output and modifies the weight and biases of inputs, and, because the input weights and biases are adjusted, the error of prediction output and observed output can be minimized. Such a process leads to backpropagation being designated an "error-minimization technique" (Rumelhart, Hinton, & Williams, 1986).

Among the various types of backpropagation ANN models, six training algorithms were investigated in this thesis:

1. Resilient Backpropagation (RP): RP directly uses local gradient information to fit the weight and bias values (Demuth & Beale, 2002; Gopalakrishnan, 2010).

2. Conjugate Gradient Backpropagation with Powell-Beale Restarts: all conjugate gradient algorithms begin by searching in the steepest descent direction (negative of the gradient) on the first iteration. A line search is then implemented to determine the optimal distance to move along the current search direction. This algorithm is highly useful for large-scale unconstrained optimization (Demuth & Beale, 2002; Gopalakrishnan, 2010).
3. Scaled Conjugate Gradient (SCG): SCG is a very efficient algorithm for large networks, because this algorithm avoids line search steps that significantly reduce the number of computations performed during each iteration (Demuth & Beale, 2002; Gopalakrishnan, 2010).
4. BFGS Quasi-Newton: The BFGS algorithm was discovered by Broyden, Fletcher, Goldfarb, and Shanno; although this algorithm often converges faster than conjugate gradient methods, it is more complex and expensive for feedforward neural networks. BFGS can be an efficient training algorithm for smaller networks (Demuth & Beale, 2002; Gopalakrishnan, 2010).
5. Levenberg-Marquardt (LM): LM backpropagation is the fastest backpropagation algorithm, and it can solve non-linear least squares and curve fitting problems (Demuth & Beale, 2002; Gopalakrishnan, 2010).
6. Bayesian Regularization (BR): BR backpropagation is another training algorithm that is updated from LM backpropagation optimization weight and bias values (Demuth & Beale, 2002; Gopalakrishnan, 2010).

2.2.4. Non-Destructive Testing (NDT) Techniques on Joint Activation

Non-destructive testing (NDT) is a method for testing, inspecting, and evaluating appliances without damaging their properties. To date, NDT techniques have been of increased interest in structural health monitoring and pavement performance evaluation (Miskiewicz, Lachowicz, Tysiac, Jaskula, & Wilde, 2018). There are many different NDT testing methods, including Ultrasonic Testing (UT), Electromagnetic Testing (ET), Laser-Testing Methods (LM), etc. Among these methods, Magnetic Particle Testing (MT), Liquid Penetrant Testing (PT), Radiographic Testing (RT), Ultrasonic Testing (UT), Electromagnetic Testing (ET), and Visual Testing (VT) are the six most popular NDT-testing methods (Baum, 2014).

In the field of civil engineering, NDT techniques represent a cost-efficient and time-saving tool for engineers and researchers to evaluate or monitor material properties and performance during a structure's service life (Villain, Garnier, Sbartaï, Derobert, & Balayssac, 2018). Several parameters can affect concrete pavement performance and service life, including concrete properties such as mechanical strength, water content, porosity, and degree of saturation (Villain et al., 2018), and construction design aspects, such as joint spacing, pavement thickness , traffic volume, etc.

Among these principal aspects, joint spacing size is one of the most significant factors affecting concrete pavement long-term performance. Contraction joints include those in both the transverse and longitudinal directions. The primary purpose of installing joints is to control cracks in concrete slabs and help relieve stresses (Raoufi, Radlinska, Nantung, & Weiss, 2008; Raoufi, Their, Weiss, Olek, & Nantung, 2009). The performance of joints is affected by joint spacing as well as saw-cut depth and timing (ACPA, 1992). According to an ACPA report (Voigt, 2000), the minimum saw-cut depth should be one-quarter of a jointed plain concrete pavement (JPCP) surface layer thickness. In addition, saw-cuts at early ages of concrete fabrication could provide joint cracking (activation) at a suitably early pavement age to help relieve stresses, but not too early because concrete pavement can deteriorate and lose material from the joints (Raoufi et al., 2008). On the other hand, joints will not activate when saw-cuts are made too late, so a pavement may absorb too much stress and have higher probability of random cracking, reducing long-term performance of concrete pavement (Raoufi et al., 2009).

In the past, coring or digging out shoulders were the only approaches available to determine whether a saw-cut had been activated, but these methods are costly and time-consuming, making it difficult to evaluate multiple joints or projects. A recent alternative is to use NDT techniques. MIRA (see in Figure 2-10) is a NDT device that uses ultrasonic shear-wave tomography and imaging to identify voids in reinforced or plain concrete. The device's antenna is comprised of a 4 by 12 array of point transducers. As shown in Figure 2-11, the device employs an ultrasonic pitch-catch method and uses an antenna composed of an array of 48 dry point-contact (DPC) transducers to create a three-dimensional (3-D) image (Popovics et al., 2017).

Figure 2-10 *MIRA device (Acoustic Control Systems 2015)*

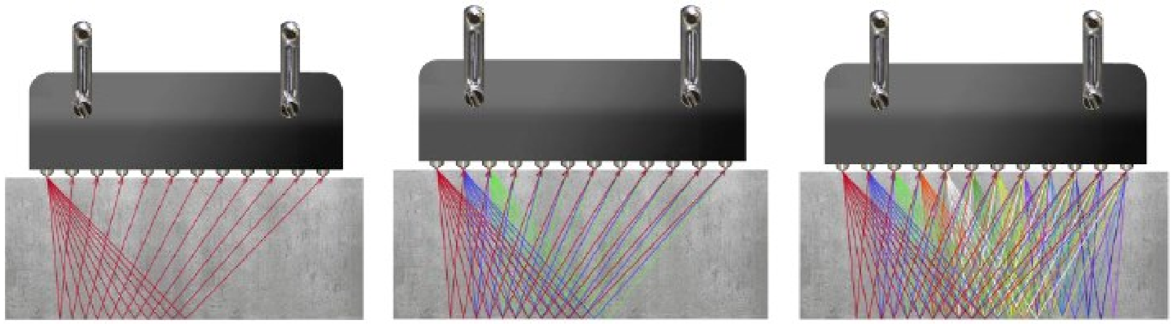


Figure 2-11 *Pitch-catch method (Acoustic Control Systems 2015)*

This technology has been used successfully for determining slab thickness, location of steel bars, detection of delamination and debonding, and for pavement deterioration investigation. To date the following five different projects have been used MIRA to evaluate and investigate concrete structure performance:

1. Thickness measurement and location of steel bar: The MIRA device can measure signal transmitting time and use a synthetic aperture-focusing technique (SAFT) for analysis in scan mode to create a 2-D image of echo intensity versus pavement depth (Hoegh, Khazanovich, & Yu, 2011). From this 2-D image, steel bar and surface thickness of concrete pavement can easily be observed (see in Figure 2-12).

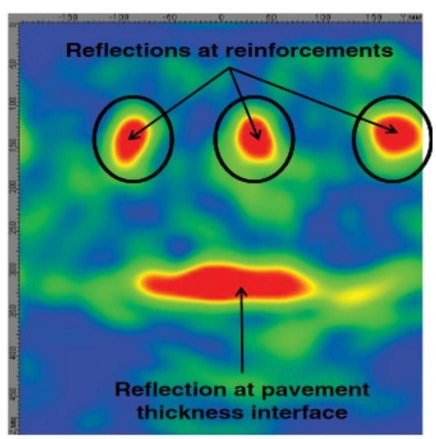


Figure 2-12 *MIRA analysis results for pavement thickness and location of steel bars* (Hoegh et al., 2011)

2. Evaluation of a two-lift concrete pavement interface that uses a lower-cost paving system below and an improved system above, with a maximum time of 90 minutes between lower and upper layer paving. The MIRA device can evaluate the bonding condition for a two-lift concrete pavement interface. As shown in Figure 2-13 the left MIRA 2-D image shows that since no reflection is measured by MIRA around the interface, the two layers are composite to on another. On the contrary, some reflections measured by MIRA close to the interface may be due to the poor bonding between two concrete layers (Tompkins, Vancura, Rao, Khazanovich, & Darter, 2011).

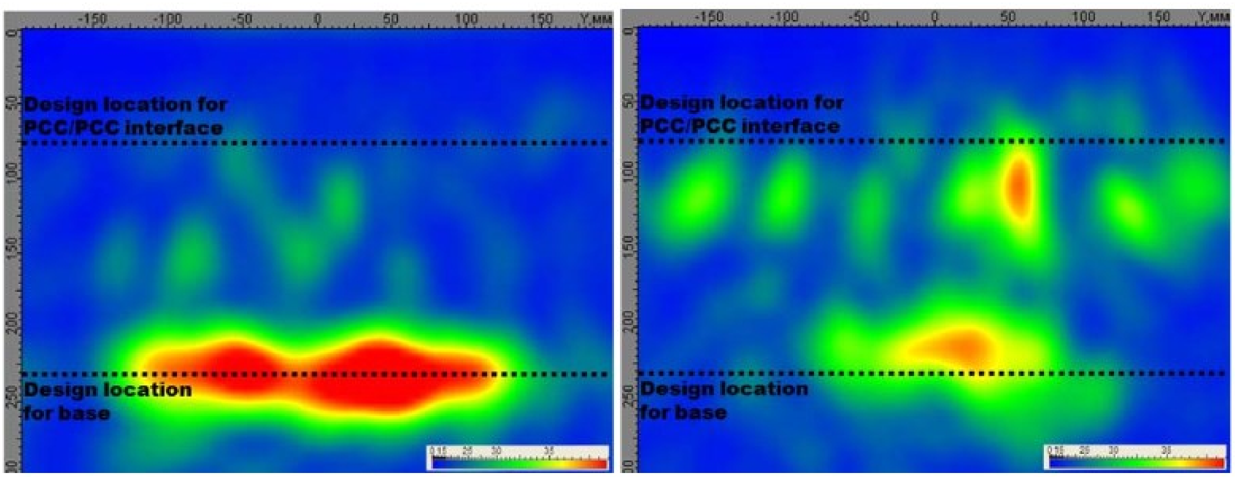
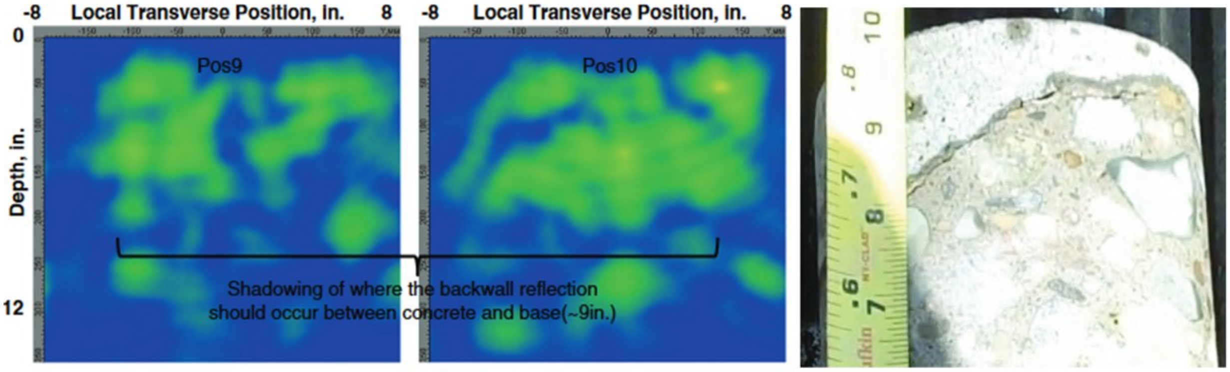


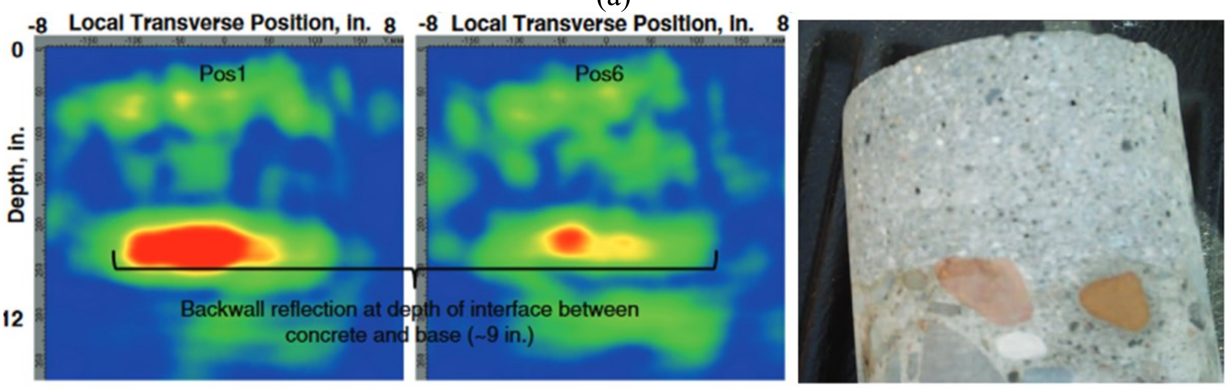
Figure 2-13 *Bonding condition for two-lift concrete pavement interface (Tompkins et al., 2011)*

3. Evaluation of repair concrete bonding performance: The MIRA device can be used to investigate the performance of bonding between concrete pavement and repair material. As shown in Figure 2-14, based on the MIRA 2-D image, since when bonding is poor the echo intensity is not large enough to reflect the full thickness of concrete pavement, the pavement thickness is difficult to observe in the 2-D image.

On the other hand, if the bonding is adequate the full pavement thickness is easy to observe in the 2-D image (Hoegh, Khazanovich, & Yu, 2012).



(a)



(b)

Figure 2-14 *Performance of bonding between concrete pavement and repair material (a) poor bonding (b) proper bonding (Hoegh et al., 2012)*

4. Detection of delamination and debonding in a concrete structure: After collecting the MIRA scan results, the 3-D visualization software can create a 3-D image for the scanning project, and this 3-D image can show the concrete structure delamination and debonding areas in Figure 2-15 (Wimsatt et al., 2012).

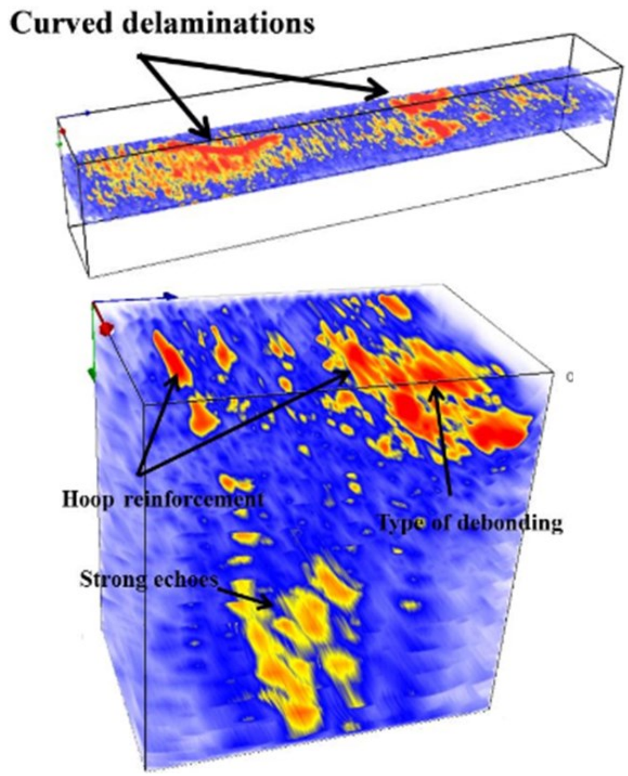


Figure 2-15 *MIRA analysis results for delaminations and debonding (Wimsatt et al. 2012)*

5. Detection of concrete cracks and deterioration: The MIRA device can also detect concrete cracks and deterioration. Echo intensity indicates a high-intensity reflection area that represents pavement thickness interface, concrete pavement deterioration, and crack location (see Figure 2-16) (Hoegh, Khazanovich, Worel, & Yu, 2013).

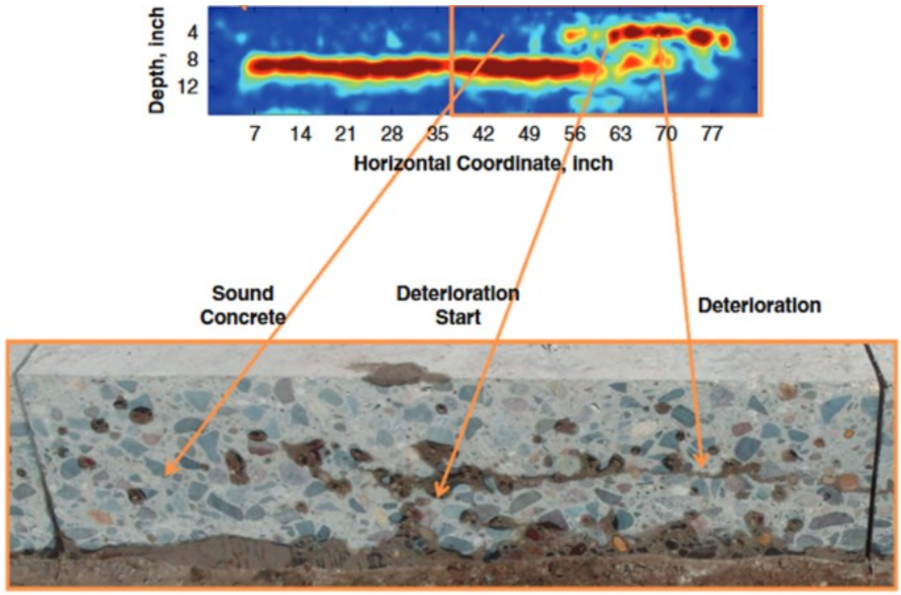


Figure 2-16 *MIRA analysis results for deterioration and crack area at concrete slab (Hoegh et al. 2013)*

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CHAPTER 3. LONG-TERM PERFORMANCE EVALUATION OF IOWA CONCRETE OVERLAYS

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3.1 Abstract

Use of concrete overlays has long been recognized as a cost-effective pavement maintenance and rehabilitation strategy. However, the long-term performance of various types of concrete overlays has not been fully investigated since there has not been enough performance data available to support such an evaluation. Concrete overlays have been regularly constructed on Iowa roadways since the late 1970s and many older projects are still in use. Performance-related data for in-service concrete overlays have been acquired from the Iowa Concrete Paving Association (ICPA), the Iowa Pavement Management Program (IPMP), and other available resources to evaluate long-term performance of concrete overlays in Iowa. The information collected includes Pavement Condition Index (PCI), International Roughness Index (IRI), overlay type, construction year, overlay thickness, joint spacing, traffic, and other construction and design-related data. Based on an evaluation of PCI and IRI (two measures representative of pavement performance) changes during service life, it is observed that concrete overlays data points can provide at least 20 years of service life. In terms of PCI ratings, 89% of data points

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investigated have PCI values greater than 60% as of the time of the analysis. Similarly, 93% of data points have IRI values lower than 2.7 m/km (170 in/mile). The effects of overlay type and design features (including overlays thickness and joint spacing) on long-term performance of Iowa concrete overlays are also discussed.

3.2 Introduction

Pavements must be well maintained and repaired if they are to continue providing good serviceability over time. One rehabilitation strategy for extending service life is to use concrete overlays (Delatte 2001). There are two major types of concrete overlays, bonded concrete overlays and unbonded concrete overlays. In general, bonded concrete overlays are used to address surface distress when the existing underlying pavement is in good or fair condition, while unbonded concrete overlays are used to rehabilitate pavements with some structural deterioration (Torres, et al., 2012).

A bonded concrete overlay should have a bond at the interface between the concrete overlay and the existing pavement so that they work as a single element. Bonded concrete overlays in Iowa include bonded concrete-on-concrete (BCOC) and bonded concrete-on-asphalt (BCOA) (Gross et al., 2017b). Bonded concrete overlays typically range in thickness from 51-mm. (2 in.) to 152-mm. (6 in.) (Torres, et al., 2012). Benefits of bonded concrete overlays include cost effectiveness, improved pavement service life, and reduced road closure time during construction (Delatte, et al., 1998). However, adequate bonding must be achieved and maintained to realize these benefits.

An unbonded concrete overlay is constructed with a debonding layer placed above the existing pavement, largely to prevent reflective cracking. Unbonded concrete overlays in Iowa include unbonded concrete-on-concrete (UBCOC) and unbonded concrete-on-asphalt (UBCOA) (Gross et al., 2017). Typical thicknesses are 102-mm. (4 in.) to 279-mm. (11 in.) (Torres, et al., 2012). Unbonded concrete overlays typically are thicker than bonded concrete overlays because the new layer must be structurally independent of the lower layer.

Potential distresses that concrete overlays may experience include material-related distresses (MRD) such as alkali-silica reaction (ASR), D-cracking, and freeze-thaw damage (Harrington, et al., 2014), and load-related distress including transverse cracking, faulting, and joint spalling (Rasmussen, et al., 2002). Existing pavement condition is also one of the most important issues affecting concrete overlay performance. The thickness and condition of the existing asphalt pavement may be especially critical in affecting concrete overlay service life (Vandenbossche et al. 2011; Mateos, Harvey, Paniagua, and Paniagua 2015). Concrete overlays should be properly designed and constructed to prevent premature deterioration.

Concrete overlays do not represent a new concept, there are also some pertinent literature evaluating concrete overlay performance. Sufficient slab thickness, small panel size, used macro-fiber and surface drainage system are important factors influencing BCOA performance (King & Roesler, 2014b). However, the long-term performance of all different types of concrete overlays has not been investigated in-depth because of a shortage of data. The aim of the work reported in this paper is to combine data available from several sources and provide guidance for proper decision-making with respect to concrete overlays design and construction.

3.3 Objective and scope

The primary objective of this study is to evaluate the long-term performance of various types of concrete overlays constructed in Iowa since the 1970s. Performance data dating back to 1998 for all in-service Iowa concrete overlays constructed over the last 38 years were collected and evaluated. Performance measures utilized in this study include the Pavement Condition Index (PCI) and International Roughness Index (IRI). The effects of overlay type and design features on long-term performance were also identified.

3.4 Methodology

3.4.1. General Iowa Concrete Overlay Projects Information

Figure 3-1 shows the spatial distribution of the 384 overlay projects included in the study. Four different types of concrete overlays have been in use in Iowa, including bonded concrete-on-concrete (BCOC), unbonded concrete-on-concrete (UBCOC), bonded concrete-on-asphalt (BCOA), and unbonded concrete-on-asphalt (UBCOA). Historically, the term whitetopping has referred to a concrete overlay of asphalt. For this study, whitetopping was divided into two categories: BCOA and UBCOA. Concrete overlays on asphalt where slab thickness was less than or equal to 152-mm (6 in.) were designated as BCOA, whereas concrete overlays on asphalt where slab thickness were more than 152-mm (6 in.) were designated as UBCOA. This division follows historical Iowa concrete overlays practices (Gross et al. 2017). A total of 35 overlays were known to have been reconstructed or replaced at the time of this study, but these were not considered in the analysis because there were no detailed records regarding when they were taken out of service. However, those 35 projects comprised fewer than 10% of all projects considered in the study. As shown in Table 3-1, 91% of the included projects were completed during the past 30 years. 82% of these projects have an average daily traffic (ADT) range below 1,500, meaning that most of these projects were on the county road system. Overlays thickness ranged from 51-mm. (2 in.) to 305-mm. (12 in.), and transverse joint spacing ranged from 0.9-m (3 ft.) to 12.2-m (40 ft.). 94% of projects had a design thickness ranging from 102-mm. (4 in.) to 203-mm. (8 in.) and 92% had a transverse joint spacing of either 1.7-1.8-m (5.5-6 ft.), 3.7-3.8-m (12-12.5 ft.), or 4.6-6.1-m (15-20 ft.).

Table 3-1 Distribution of Iowa Concrete Overlay Projects

Age (year)	**Percent of data based on number of projects (%)**	**ADT (count)**	**Percent of data based on number of projects (%)**	**Concrete overlays thickness (mm.)**	**Percent of data based on number of projects (%)**	**Joint spacing (m.)**	**Percent of data based on number of projects (%)**
0-2	8	<500	32	>76	2	<1.5	1
3-5	25	501-1,000	34	102	13	1.7-1.8	12
6-10	12	1,001-1,500	16	127	9	2.1-3.5	5
11-15	14	1,501-2,000	5	152	48	3.7-3.8	31
16-20	9	2,001-3,000	5	178	11	4.0-4.3	1
21-25	14	3,001-4,000	2	203	13	4.6-6.1	49
26-30	9	4,001-10,000	4	229	2	12.2	1
>31	9	>10,000	2	254	2		
Total	100	Total	100	Total	100	Total	100

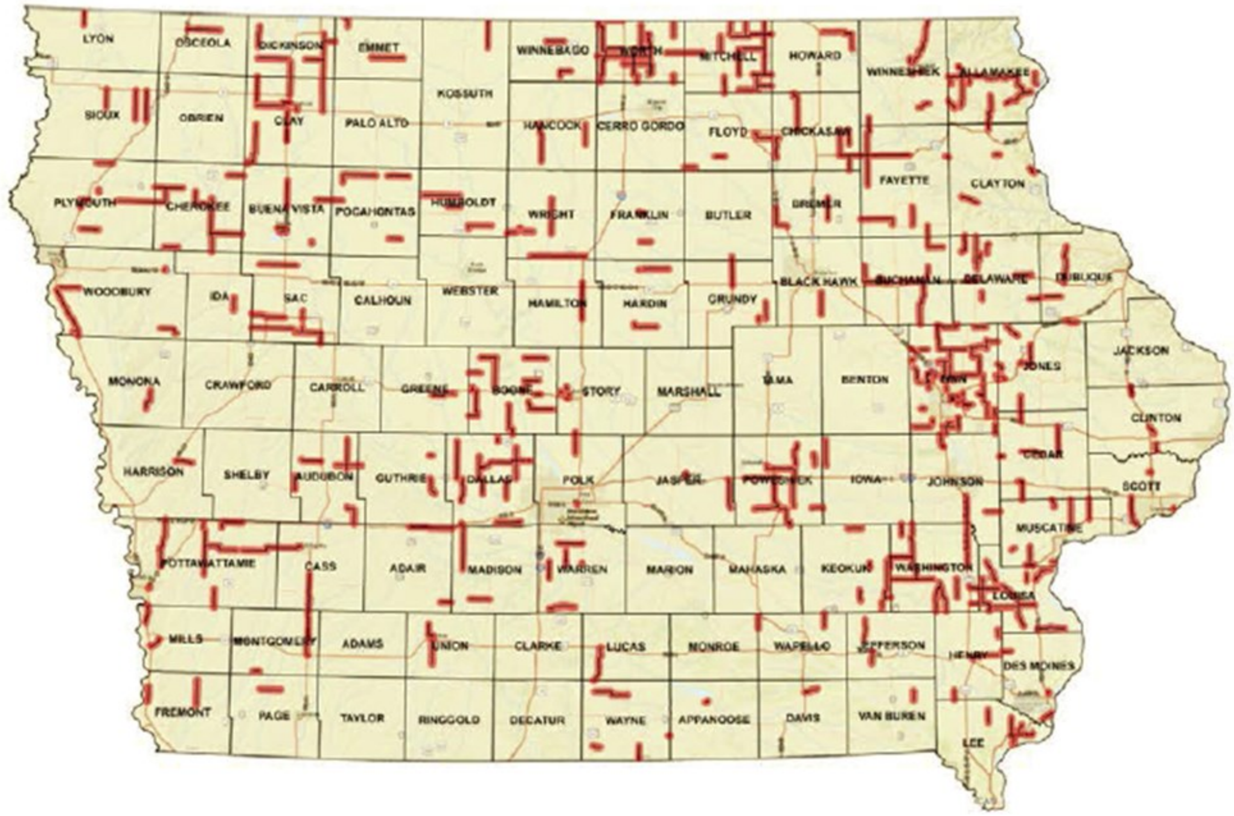

Figure 3-1 *Spatial distribution of Iowa concrete overlay projects*

3.4.2. Iowa Concrete Overlay Field Performance Data

Concrete overlay performance data were obtained from pavement distress databases maintained by the Iowa Pavement Management Program (IPMP). The IPMP has collected data on state and local highways since 1998. The pavement distress data was collected by a vendor using an automatic road analyzer (ARAN). Prior to 2011, the distress data were collected at a spacing of 10 m. (32.8 ft.) for 100% coverage of the pavement management section. Since 2011, the distress data have been collected at a spacing of 16 m (52.5 ft.). The data used spanned a 16-year interval. In addition to pavement distress data, project data was collected from the Iowa Concrete Paving Association (ICPA), which included joint spacing, overlay thickness, type of overlay, traffic volumes, and year of overlay construction.

The concrete overlay pavement performance data included distresses such as transverse cracking, longitudinal cracking, faulting, D-cracking, joint spalling, and International Roughness Index (IRI), among others. Average left wheel path and right wheel path IRI data was reported for each of the 10 m. (32.8 ft.), or 16 m (52.5 ft.) sections, depending on the year of collection. The linear lengths of longitudinal wheel path and non-wheel path, as well as transverse cracking and area of patching, were summed and reported, along with evaluations of low, medium, and high levels of severity for every 10 m. (32.8 ft.) or 16 m. (52.5 ft.) section. Using these pavement condition data, the IPMP calculates the PCI for each concrete overlay project using Equation 1 (Gross et al. 2017).

$$PCI = 100 - 35\left(\frac{IRI}{253}\right) - 25\left(\frac{\#\ of\ D{-}crack\ joints\ per\ 528\ ft}{8}\right) - 15\left(\frac{\#\ of\ spalled\ joints\ per\ 528\ ft}{9}\right) - 25\left(\frac{\#\ of\ transverse\ cracks\ per\ 528\ ft}{14}\right) \quad (1)$$

3.5 Results and discussion

3.5.1. Performance of Concrete Overlays

Table 3-2 presents PCI distributions for the entire concrete overlay projects database and for the different types of overlays: bonded concrete on concrete (BCOC), unbonded concrete on concrete (UBCOC), bonded concrete on asphalt (BCOA), and unbonded concrete on asphalt (UBCOA).

From Table 3-2, based on PCI ratings, almost 90% of all data points constructed in Iowa are in Good to Excellent condition (i.e., in a PCI range of 60% to 100% according to the IPMP) when overlays were in their first 10 years of service. Among the different concrete overlay types and years of service,

- First 10 years of service: all four types of concrete overlays showed similar performance.

- During 11 to 20 years of service: UBCOC, BCOA and UBCOA performed better than BCOC.
- During 21 to 30 years of service: BCOA and UBCOA performed better than UBCOC.
- For more than 30 years of service: UBCOA performed better than BCOA.

It appears that UBCOAs performed better than BCOAs in terms of PCI values. Overlays of asphalt appeared to perform better than overlays of concrete.

Table 3-2 Different Age Range PCI Distribution for Iowa Concrete Overlays Data

Type of overlays	**Distribution of data points in Excellent to Good condition (%)**			
	Age (year)			
	0-10	11-20	21-30	>31
BCOC (Bonded concrete on concrete)	89	50	-	-
UBCOC (Unbonded concrete on concrete)	100	85	58	-
BCOA (Bonded concrete on asphalt)	97	94	80	59
UBCOA (Unbonded concrete on asphalt)	99	96	89	80

Figure 3-2 and Figure 3-3 show PCI and IRI distributions of Iowa concrete overlays over the last 38 years. Although, the data set is noisy, and the coefficient of determination (R^2) are poor, PCI and IRI trends appear to be valid. As seen in Figure 3-2 and Figure 3-3, the PCI data, follows a downward trend while the IRI data follows an upward trend as the overlays age, both as expected. Based on the PCI data illustrated in Figure 3-2, concrete overlay performance can be rated on average, from Excellent to Good during the first 34 years of service before trending below 60% into Fair condition.

Acceptable initial International Roughness Index (IRI) values for newly-constructed PCC pavements range between 1.00 m/km (63 in/mile) and 1.18 (75 in/mile) in Iowa (Iowa DOT, 2016). Based on the IRI data illustrated in Figure 3-3, the IRI trend line did not increase above an unacceptable value of 2.7 m/km (170 in/mile) during 38 years of service (Arhin, et al., 2015).

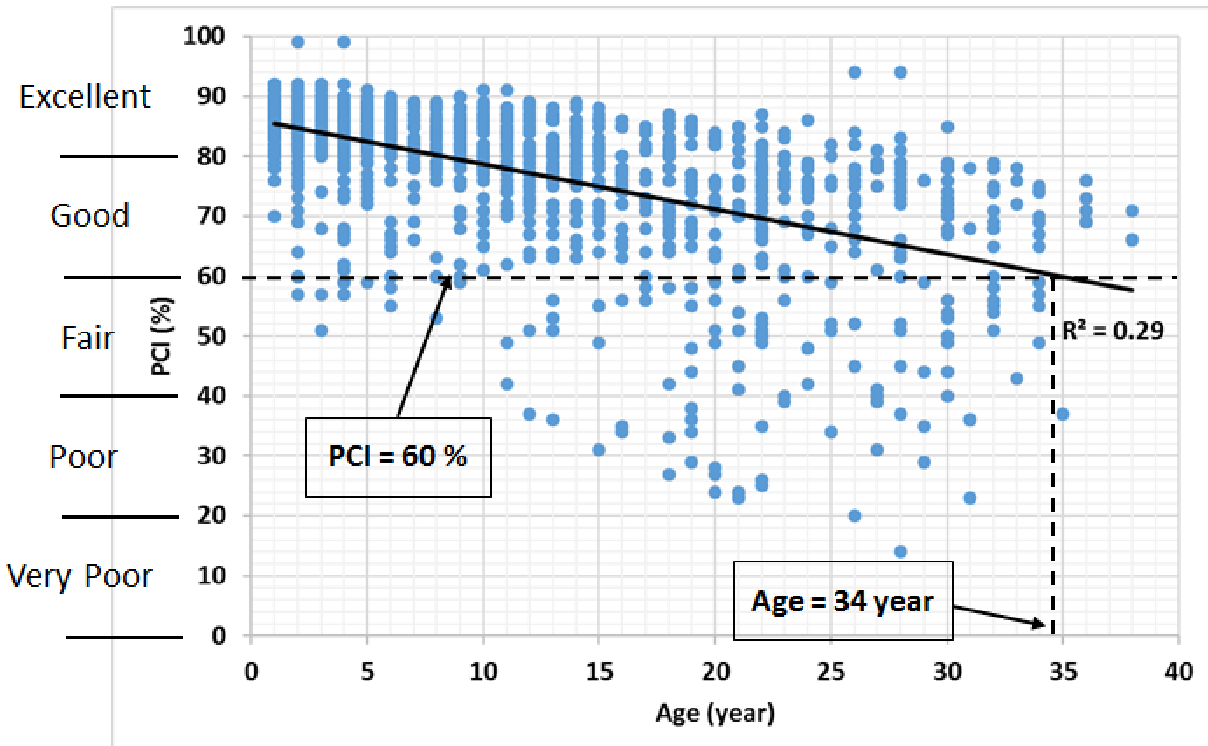

Figure 3-2 *Iowa concrete overlays PCI measure history for all projects*

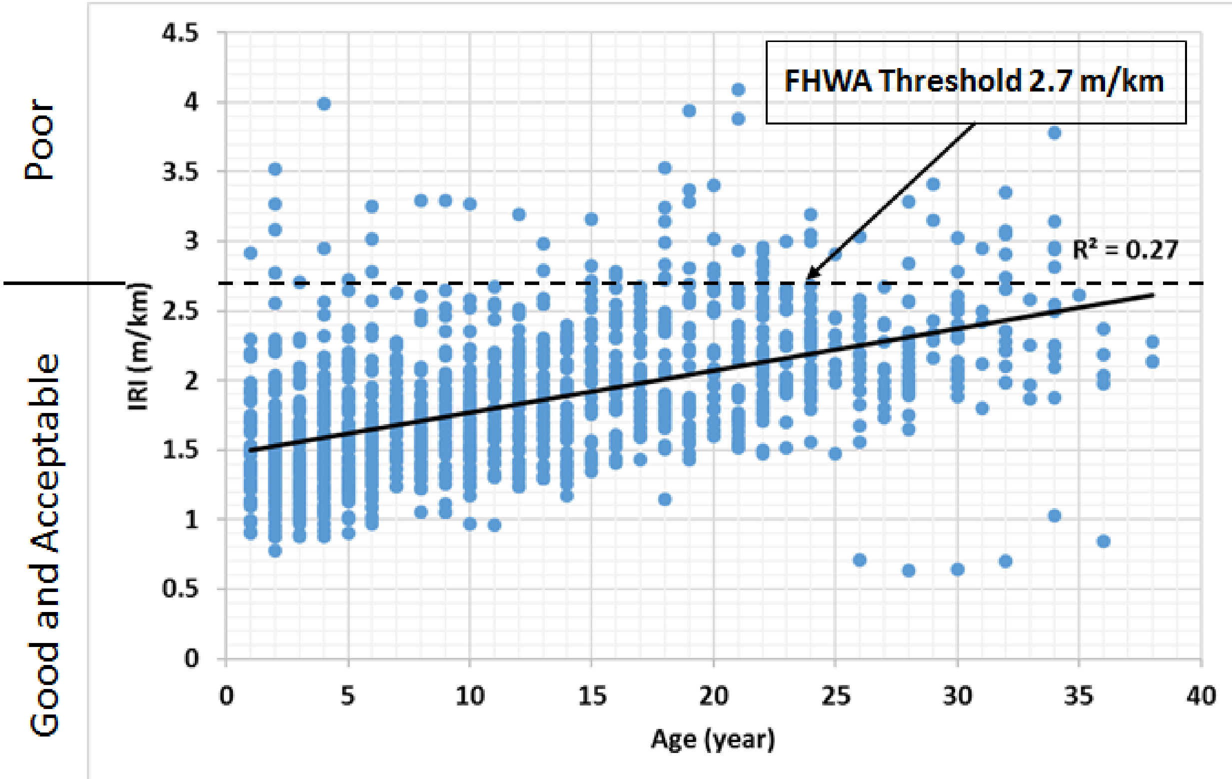

Figure 3-3 *Iowa concrete overlays IRI measure history for all projects*

3.5.2. Effect of Overlay Type on Concrete Overlay Performance

Figure 3-4 displays changes in PCI with age for each type of concrete overlay.

Based on the PCI trend in Figure 3-4a, BCOC were above 60% (Good to Excellent) during the first 12 years of service. Figure 3-4b illustrates that the PCI trend of UBCOC dropped below 60% after 23 years of service. Figure 3-4c and Figure 3-4d illustrate changes in PCI values with age for BCOA and UBCOA, respectively. The PCI trends of BCOA and UBCOA did not fall below 60% during the first 38 years of service.

Similar to Figure 3-2 and Figure 3-3, the data set in Figure 3-4 is noisy and the correlation coefficients are poor, but these trends indicate that the BCOA and UBCOA PCI trends change with age at a lower rate compared to those of BCOC and UBCOC. Also, between the two types of overlays of asphalt, UBCOA in general has a longer service life than BCOA.

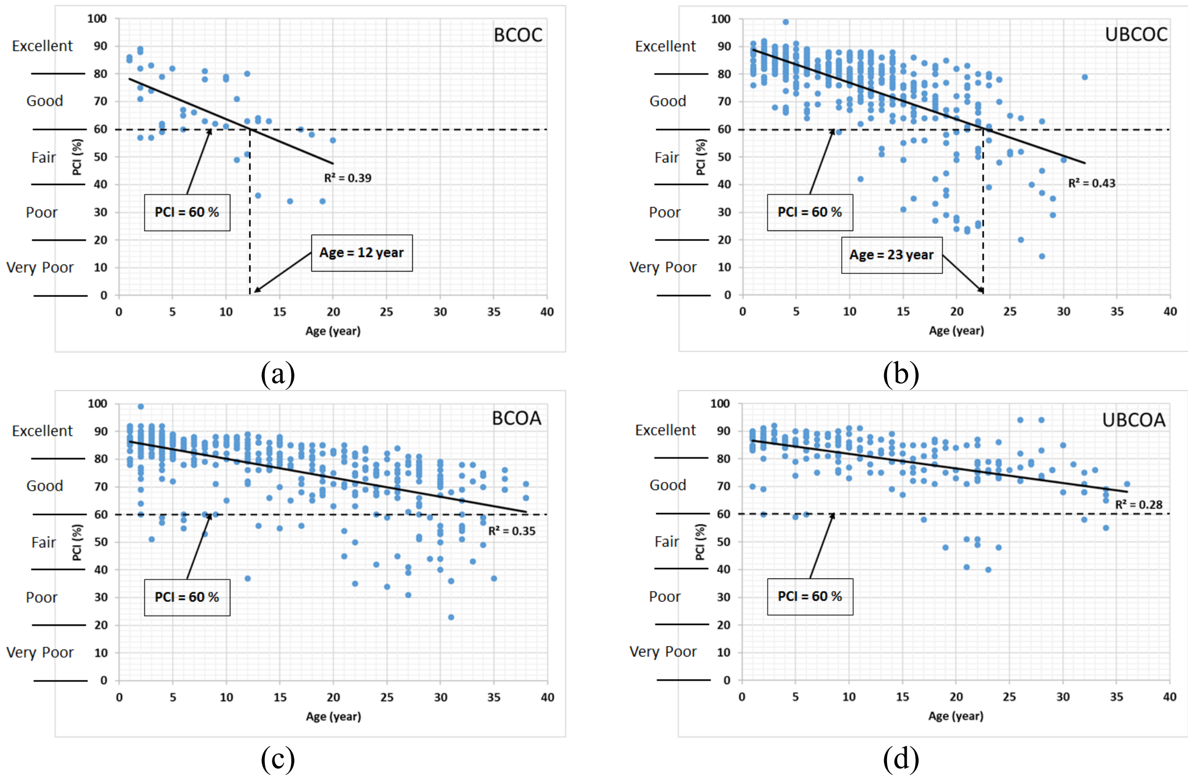

Figure 3-4 *Iowa concrete overlays PCI history categorized by overlays types: (a) BCOC, (b) UBCOC, (c) BCOA, and (d) UBCOA*

Figure 3-5 shows IRI changes with age for each type of concrete overlay.

As seen in Figure 3-5a, the IRI trend line for BCOC remains below 2.7 m/km (170 in/mile) during the first 20 years of service. Figure 3-5b illustrates that IRI values of UBCOC significantly increased with age to greater than 2.7 m/km (170 in/mile) after 27 years.

According to Figure 3-5c and Figure 3-5d, IRI values of BCOA and UBCOA also increased slowly with age, remaining below 2.7 m/km (170 in/mile) during the full-service life.

These observations indicate that most Iowa concrete overlays perform well in terms of IRI values.

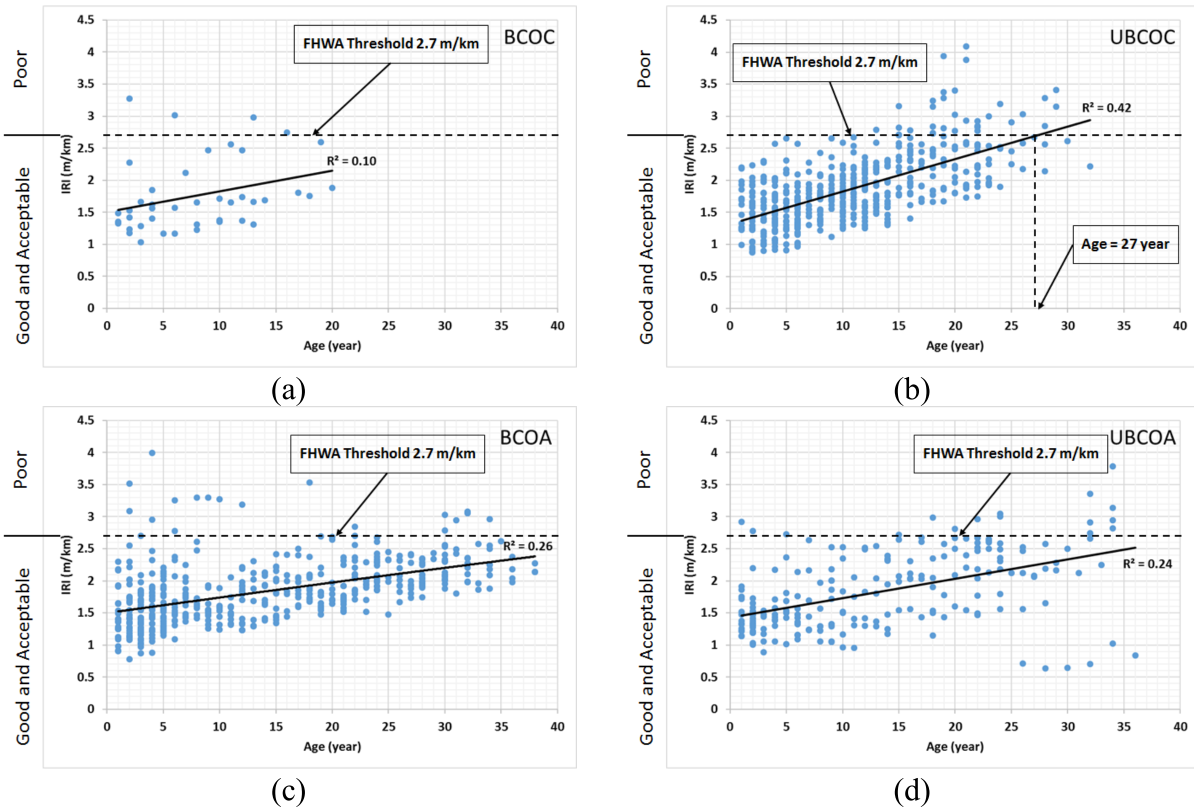

Figure 3-5 *Iowa concrete overlays IRI history categorized by type of overlays: (a) BCOC, (b) UBCOC, (c) BCOA, and (d) UBCOA*

3.5.3. Effect of Average Daily Traffic on Concrete Overlays Performance

Figure 3-6 and Figure 3-7 show changes in PCI and IRI values with age under various traffic conditions.

According to Table 3-1, projects with more than 1,500 ADT accounted for only 18% of the projects. With limited data for higher traffic volumes, PCI variation with age could not be clearly identified.

Based on Figure 3-6, the PCI values categorized by traffic levels decreased with age and, in general, most of the data sets (90% of data points) remained above 60% during the 38 years of service. This result must be qualified because of the low traffic volumes carried by most of the roadways analyzed in this study.

Figure 3-7 illustrates changes in IRI values with age. Similar to findings for PCI, the traffic level was not found to be a significant factor influencing changes in IRI values in this study. Historically, concrete overlays have been designed without taking traffic-related variables into account (Harrington et al. 2007).

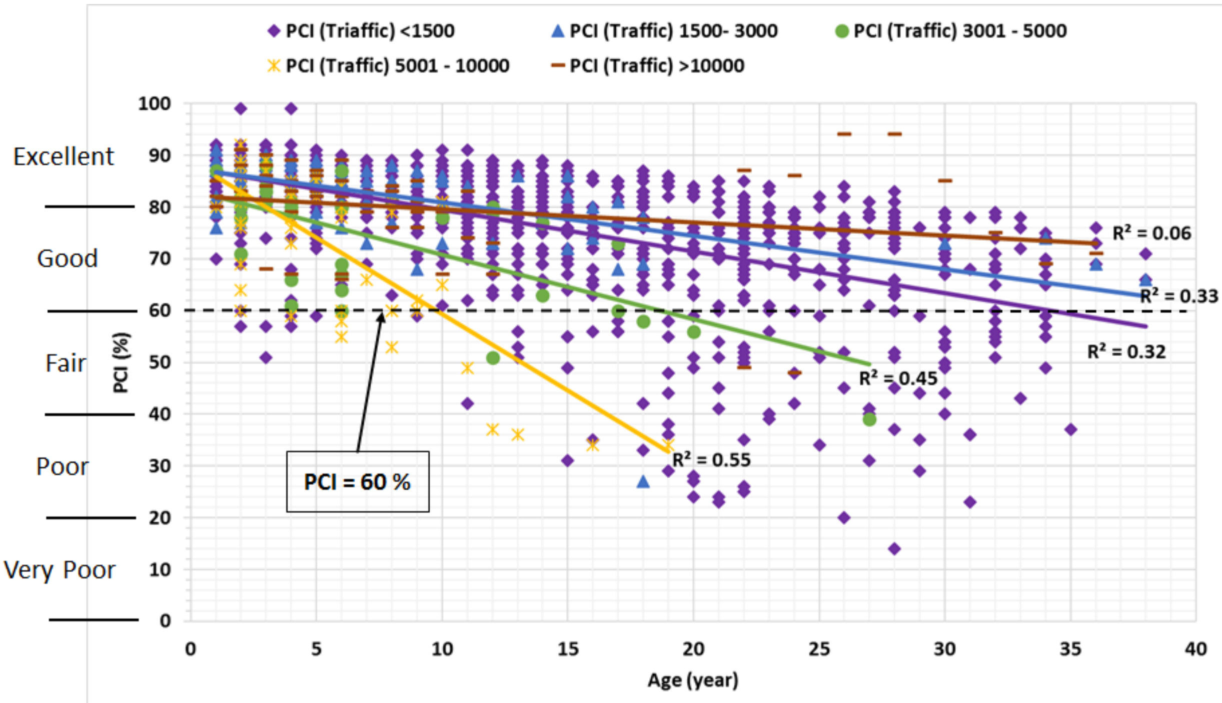

Figure 3-6 *Iowa concrete overlays PCI history categorized by traffic*

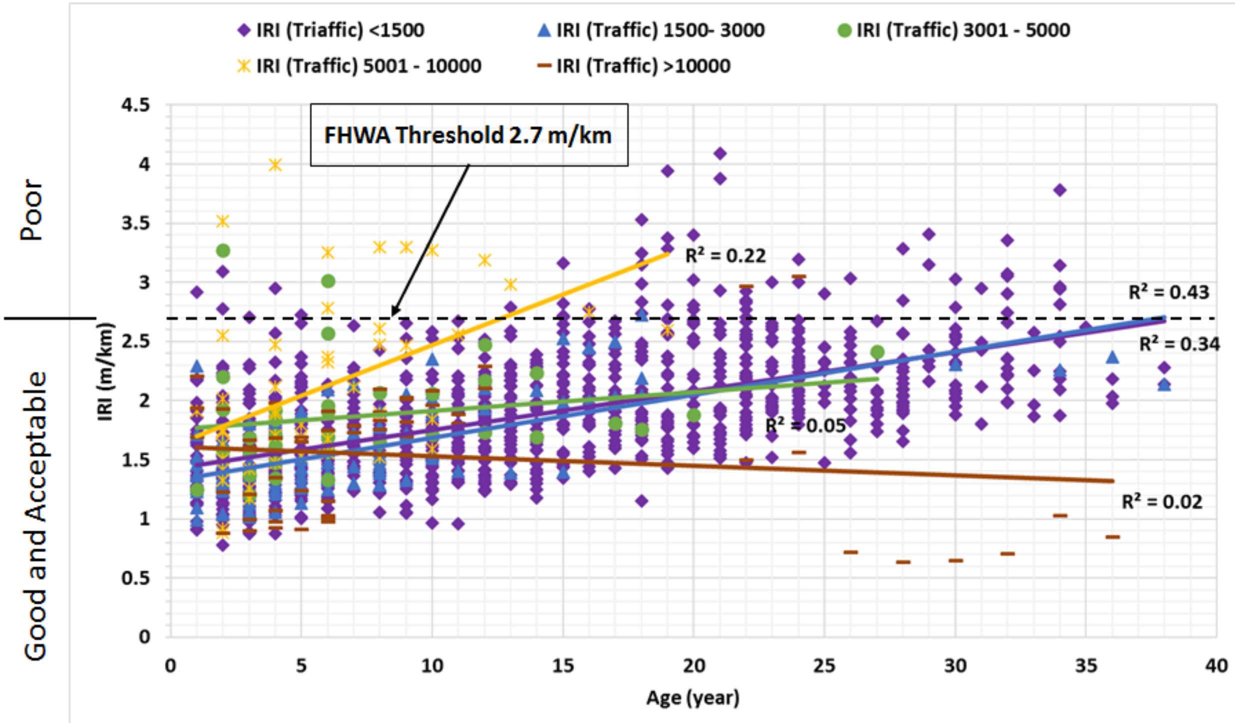

Figure 3-7 *Iowa concrete overlays IRI history categorized by traffic*

3.5.4. Effect of PCC Slab Thickness on Iowa Concrete Overlay Performance

Figure 3-8 shows changes in PCI values with age for different overlay thicknesses, separated based on overlay type. Note that the individual plots in Figure 3-8 do not each include all types of concrete overlays, since each overlay type has a different thickness range.

Figure 3-8a presents changes in PCI values for two overlays types (BCOC and BCOA) in the 102-mm. (4 in.) overlays thickness range. Although the coefficient of determination (R^2) is low, it can be concluded based on PCI values that BCOA performed better than BCOC, and BCOAs had a longer service life.

As seen in Figure 3-8b, at the 127-mm. (5 in.) overlay thickness range, the PCI values for BCOA remained above 60% during the first 30 years of service, while PCI values for UBCOC dropped below 60% after just 20 years of service.

From Figure 3-8c, it can be observed that the 152-mm. (6 in.) PCC slab thickness group has more data points than other thickness. Data were available for two different overlay types: BCOA and UBCOC. The BCOA remained above 60% after the 38 years of service. On the other hand, the trend of UBCOC dropped below 60% after 23 years. Similar to other figures, R^2 values were low, but the trends showed BCOA performed better than UBCOC in this thickness category.

Figure 3-8d and Figure 3-8e present PCI values for UBCOA and UBCOC in the 178-mm. (7 in.) and 203-mm. (8 in.) slab thickness ranges, respectively. At these thicknesses, the trends show that UBCOA performed better than UBCOC and that PCI did not change much with age. The PCI trend of UBCOC remained above 60% during the first 20 years of service, while the PCI trend of UBCOA remained above 60% during the first 35 years of service.

Together, these observations from Figure 3-8 indicate that thicker concrete overlays tend to perform better. When overlay thickness is between 102-mm. (4 in.) and 203-mm. (8 in.), the PCI trends of UBCOC, BCOA, and UBCOA were all above 80% during the first 10 years of service.

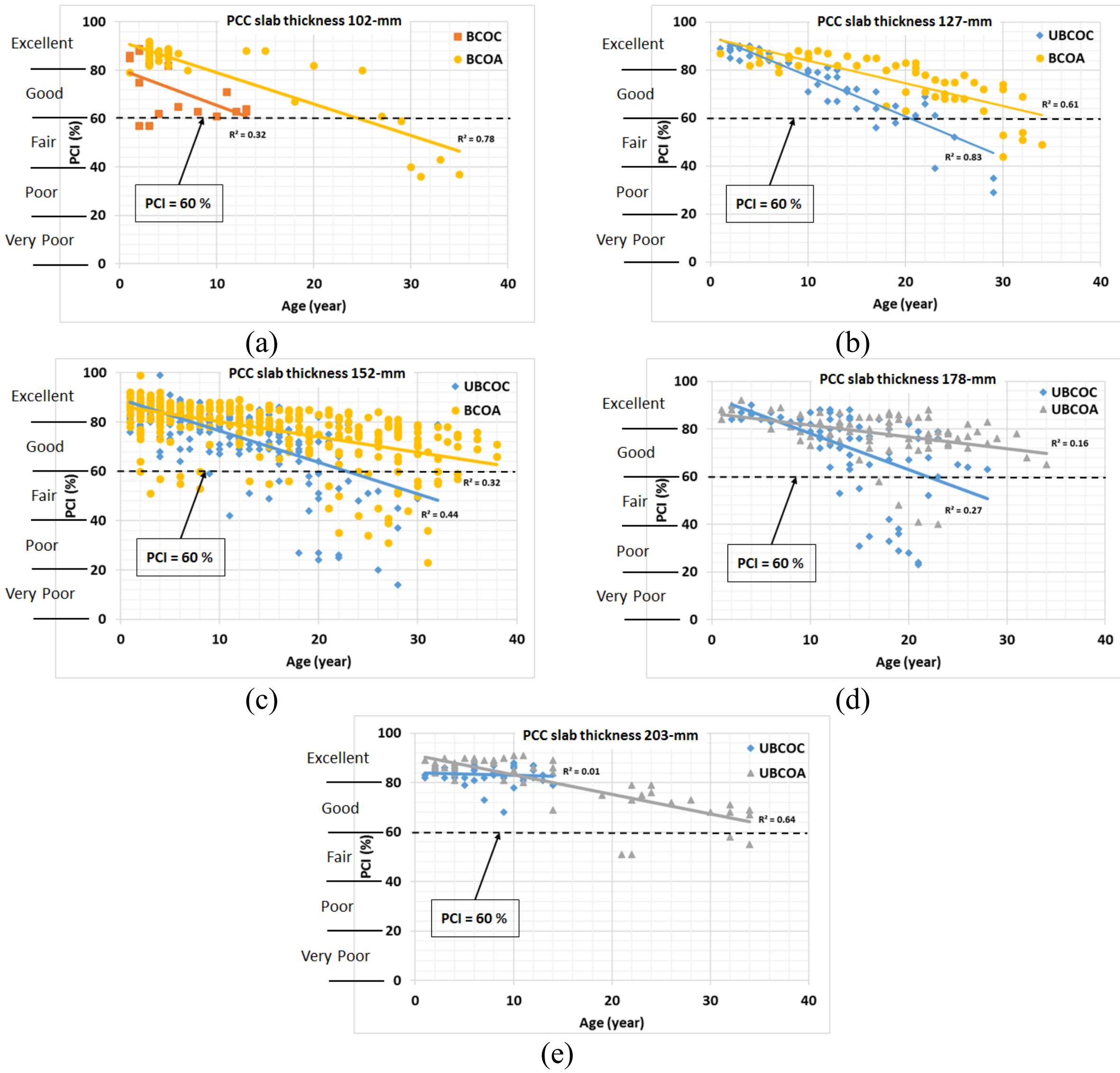

Figure 3-8 *Iowa concrete overlays PCI history categorized by thickness (cube marker: BCOC, diamond marker: UBCOC, circle marker: BCOA, triangle marker: UBCOA): (a) PCC slab thickness 102-mm, (b) PCC slab thickness 127-mm, (c) PCC slab thickness 152-mm, (d) PCC slab thickness 178-mm, and (e) PCC slab thickness 203-mm*

Figure 3-9 presents changes in IRI values with age for overlays thicknesses, separated based on overlay type.

According to Figure 3-9a, IRI for BCOC did not change much with age, while IRI for BCOA increased more quickly than BCOC. For both of these overlay types, IRI values did not exceed 2.7 m/km (170 in/mile) during 35 years of service. As a result, in terms of IRI trends, BCOC performed better than BCOA.

Based on Figure 3-9b and Figure 3-9c, the IRI of BCOA increased gradually with age when the overlays thicknesses were 127-mm. (5 in.) and 152-mm. (6 in.), respectively. As seen in these figures, about 90% of projects did not exceed an IRI of 2.7 m/km (170 in/mile) during 35 years of service. BCOA and UBCOC had similar IRI values during the first 10 years of service, but the IRI trend of UBCOC rose more quickly than BCOA, so in terms of IRI BCOA performed better than UBCOC over the long-term.

Figure 3-9d presents data for the 178-mm. (7 in.) overlays thickness range. The UBCOA and UBCOC had similar IRI values during the first 10 years of service, but IRI values for UBCOC increased at a greater rate than UBCOA, so the UBCOA performed better than UBCOC in terms of IRI in the long-term. Figure 3-9e indicates that IRI for UBCOC did not change with age when the overlays thickness was 203-mm. (8 in.). This is probably due to lack of data for this relatively higher thickness. On the other hand, IRI for UBCOA did increase with age, with four IRI data points higher than 2.7 m/km (170 in/mile). Together, these observations from Figure 3-9 indicate that, with respect to of IRI trends, thicker concrete overlays perform better.

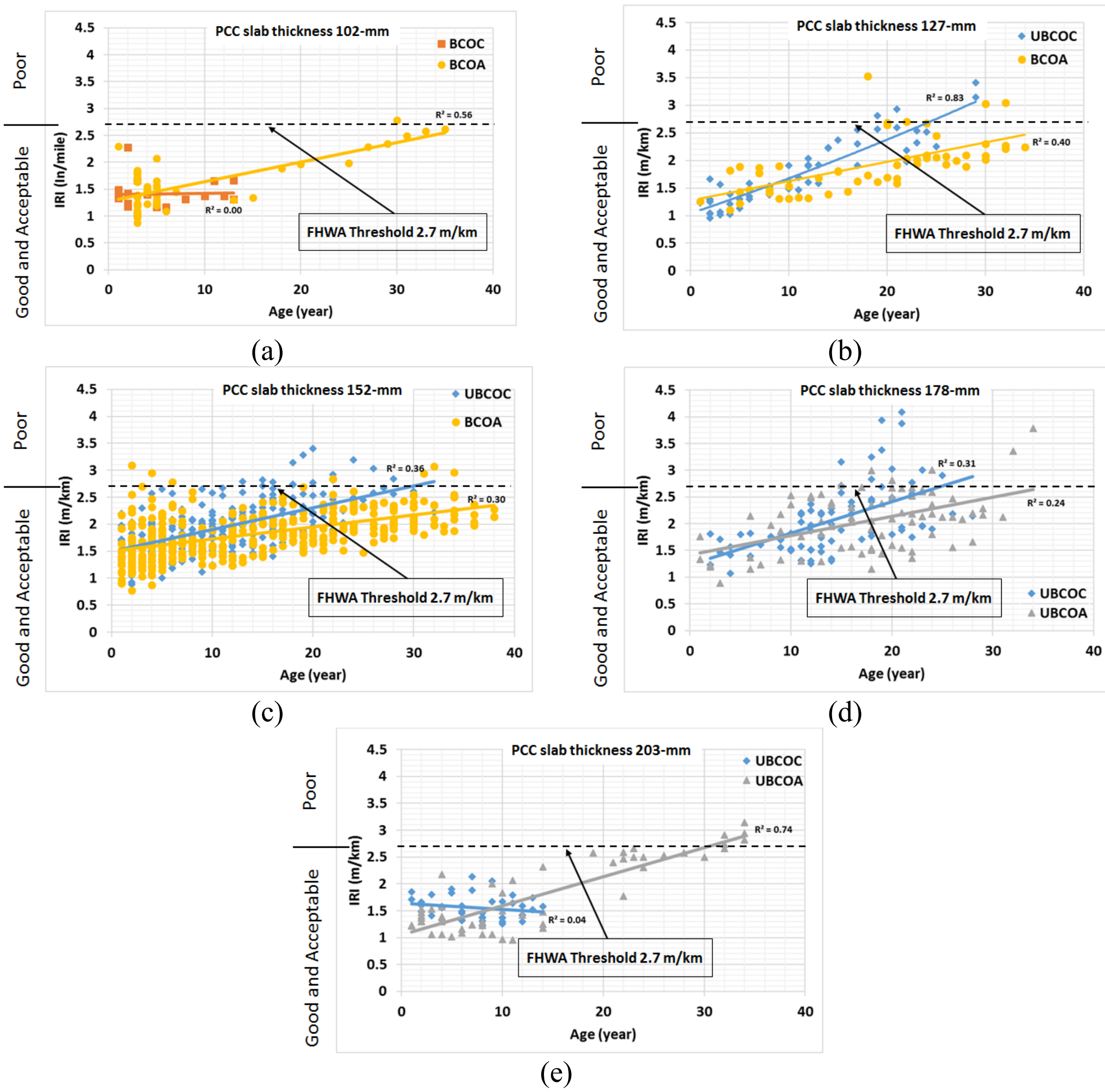

Figure 3-9 *Iowa concrete overlays IRI history categorized by thickness (cube marker: BCOC, diamond marker: UBCOC, circle marker: BCOA, triangle marker: UBCOA): (a) PCC slab thickness 102-mm, (b) PCC slab thickness 127-mm, (c) PCC slab thickness 152-mm, (d) PCC slab thickness 178-mm, and (e) PCC slab thickness 203-mm*

3.5.5. Effect of Joint Spacing on Iowa Concrete Overlays Performance

Figure 3-10 shows changes in PCI values with age for different transverse joint spacing types. Similar to Figure 3-8 and Figure 3-9, the individual plots in Figure 3-10 do not cover all concrete overlay types because particular joint spacing were sometimes only used on certain types of overlays.

Based on Figure 3-10a, the PCI trends for BCOA and UBCOC were greater than 60% during the first 10 years of service when using 1.7-1.8 m. (5.5-6 ft.) of transverse joint spacing.

Based on Figure 3-10b, BCOA performed better than other types of overlays in terms of PCI trends for 3.7-3.8 m. (12-12.5 ft.) transverse joint spacing. In the first 10 years of service, the PCI values for UBCOC and UBCOA were close to one another, but the PCI of UBCOA dropped more rapidly over time than UBCOC, indicating that UBCOC performed better than UBCOA in the long-term.

Figure 3-10c presents PCI data for a 4.6-6.1 m. (15-20 ft.) joint spacing range for different types of overlays. BCOA and UBCOA performed better than BCOC and UBCOC. PCI values for UBCOC, BCOA and UBCOA are close to one another during the first 10 years of service, but PCI of BCOC is lower than the other types of overlays over the first 10 years and decreased more rapidly than BCOA and UBCOA over time.

Shorter joint spacing reduces concrete slab tensile stresses, so smaller slab sizes are recommended over larger ones (Mack, et al., 1998). Previous studies have recommended that the length and width of joint spacing in feet for concrete overlays should be no more than 1.5 times the thickness in inches; for overlays equal to or less than 152-mm. (6 in.), therefore, the recommended joint spacing is 2.7-m (9 ft.).

These studies indicate that the joint spacing is an important parameter influencing concrete overlay performance and that shorter slab sizes (transverse joint spacing between 1.7 m. and 1.8 m.) should provide better performance for concrete overlays than longer slab sizes. Shorter concrete overlays slab sizes have only been used in Iowa during the last ten years, and they have demonstrated good performance to-date based on the results in Figure 3-10. Performance data from the older Iowa concrete overlays in Figure 3-10 have also shown that larger slab sizes (transverse joint spacing higher than 3.7 m.) can also deliver good long-term performance, particularly when used in BCOA and UBCOA applications.

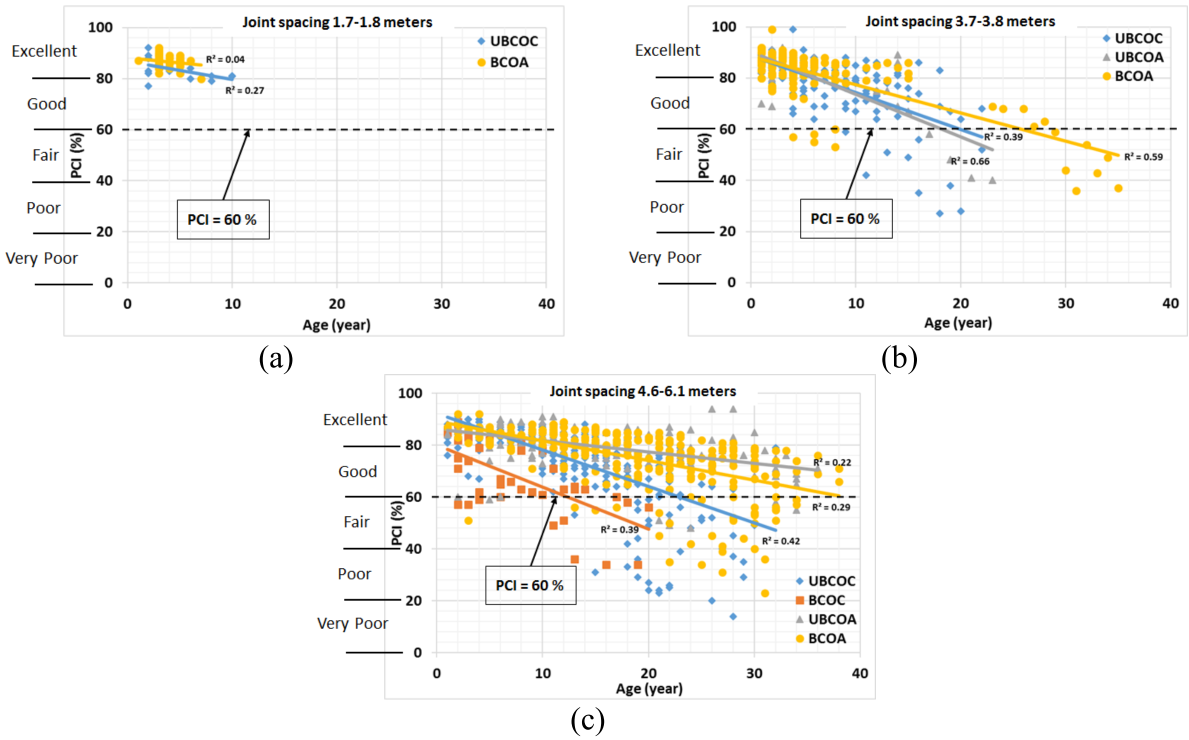

Figure 3-10 *Iowa concrete overlays PCI history categorized by joint spacing (cube marker: BCOC, diamond marker: UBCOC, circle marker: BCOA, triangle marker: UBCOA): (a) joint spacing 1.7-1.8 meters, (b) joint spacing 3.7-3.8 meters, and (c) joint spacing 4.6-6.1 meters*

Figure 3-11 shows changes in IRI values with age for different joint spacing types. According to Figure 3-11a, the IRI values of UBCOC and BCOA increased with age, but with the lack of long-term data, IRI values overall did not increase much and remained below 2.7 m/km (170 in/mile).

Figure 3-11b illustrates the relationship between IRI values and age for the 3.7-3.8 m. (12-12.5 ft.) joint spacing range. While three different overlays types' IRI values are close to one another during the first 10 years, the IRI trend of BCOA increased more gradually compared to those of UBCOC and UBCOA, indicating that BCOA performed better than UBCOC and UBCOA in the long-term. Figure 3-11c illustrates the relationship between IRI and age for a 4.6-

6.1 m. (15-20 ft.) joint spacing range. Four different overlays types' IRI trends were close to one another during the first 10 years of service, with the IRI of UBCOC increasing more rapidly with age than other overlays types. IRI of UBCOA and BCOA did not change much with age.

Some observations indicate that concrete overlay performance may suffer when thinner slabs and large slab sizes are used together, but most concrete overlay projects in this data set have IRI values below 2.7 m/km (170 in/mile) and performance trend lines for different joint spacing are close to one another. Changes in IRI values with age for BCOA are much slower than those of other overlays types.

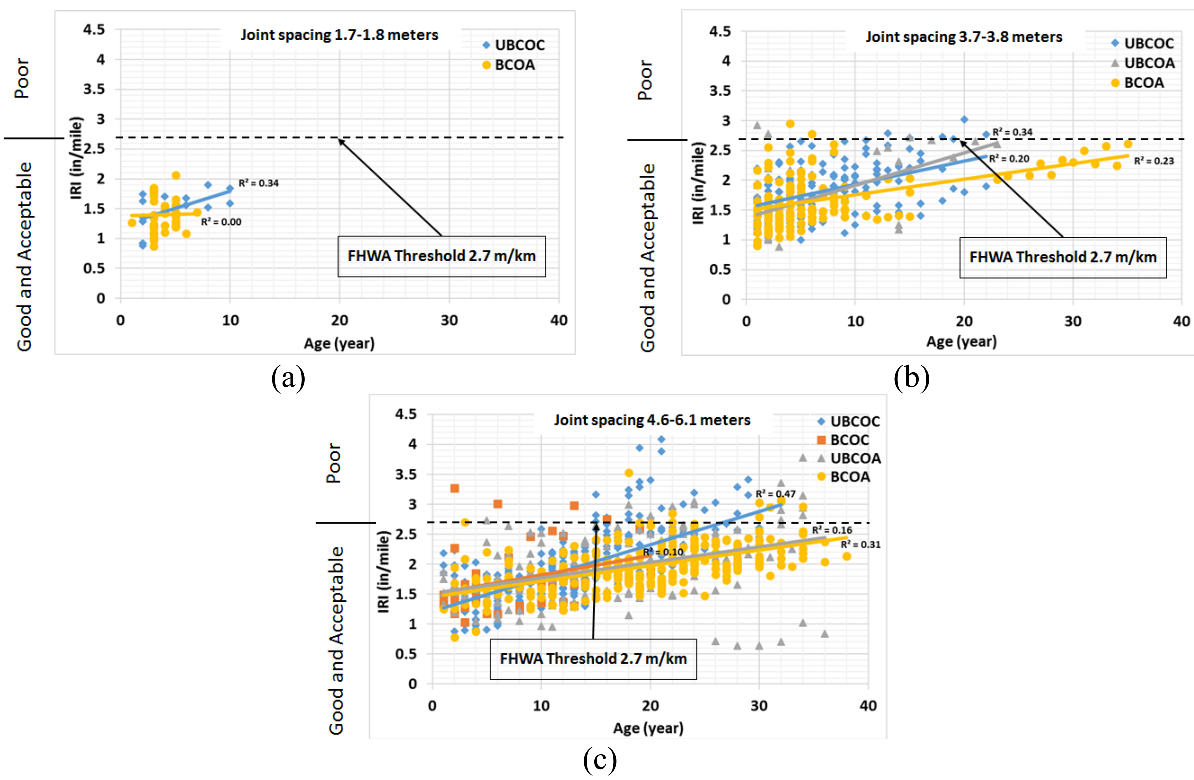

Figure 3-11 *Iowa concrete overlays IRI history categorized by joint spacing (cube marker: BCOC, diamond marker: UBCOC, circle marker: BCOA, triangle marker: UBCOA): (a) joint spacing 1.7-1.8 meters, (b) joint spacing 3.7-3.8 meters, and (c) joint spacing 4.6-6.1 meters*

3.6 Conclusions

This study evaluated the long-term performance of various types of concrete overlays built in Iowa over the last 38 years. Historical performance data for in-service concrete overlays in Iowa were collected through ICPA records and the IPMP database. This information includes PCI, IRI, overlay type, construction year, overlay thickness, joint spacing, traffic levels, and other construction- and design-related information. Changes in PCI and IRI during service life have been investigated as performance change indicators. The effects of overlay types and design features (including overlay thickness and joint spacing) on long-term performance were also identified. The major findings can be summarized as follows:

- According to PCI ratings, 89% of concrete overlay projects have PCI values greater than 60%. About 93% of concrete overlay projects have IRI values lower than 2.7 m/km (170 in/mile). This finding indicates that concrete overlays are effective in expanding the service life of existing pavements. For example, the PCI values of UBCOCs were higher than 60% up to 20 years, and the IRI values of UBCOCs were lower than 2.7 m/km (170 in/mile) up to 25 years. The PCI values of UBCOA and BCOA were higher than 60% up to 35 years, and the IRI values of UBCOA and BCOA were lower than 2.7 m/km (170 in/mile) up to 35 years.
- Performance and service life varied for different types of concrete overlays. In the first 10 years of service: all four types of concrete overlays showed similar performance. During 11 to 20 years of service: UBCOC, BCOA and UBCOA performed better than BCOC. Between 21 and 30 years of service: BCOA and UBCOA performed better than UBCOC. For more than 30 years of service: UBCOA performed better than BCOA.
- Pavement thickness can affect concrete overlay performance and service life. In general, greater overlay thickness leads to increased service life. UBCOA can provide better performance in terms of PCI and IRI trends than other concrete overlays types. UBCOC is a concrete overlay type with a broader thickness range (from 127-mm. (5 in.) to 203-

mm. (8 in.)) than the other concrete overlays types. Performance of UBCOC is similar to UBCOA in the thickness ranges of 152-mm. (6 in.) to 203-mm. (8 in.).

- Joint spacing can also affect concrete overlay performance and service life. Shorter joint spacing (i.e., 1.7-1.8 m. (5.5-6 ft.)) for UBCOC may present more advantages than larger joint spacing (i.e., longer than 3.8 m. (12 ft.)), but BCOA and UBCOA projects with joint spacing larger than 4.6 m. (15 ft.) still show performance comparable to joint spacing shorter than 4.6 m. (15 ft.).

3.7 Acknowledgements

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CHAPTER 4. EFFECT OF JOINT SPACING AND PAVEMENT THICKNESS ON CONCRETE OVERLAY PERFORMANCE

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4.1 Abstract

Concrete overlays provide cost-effective maintenance and rehabilitation strategies for pavement systems. A database has been developed in Iowa that records the historical performance of overlays based on records of International Roughness Index (IRI) and Pavement Condition Index (PCI) over a 20-year period. Based on these data concrete overlay service life has been modeled for various joint spacing. The data demonstrate that durability and service life can be improved. A review of PCI data indicates that improving construction quality to eliminate premature failure has the potential to add at least 10 years to the service life of PCC overlays.

Even though concrete overlay technology is not a new concept, most of its design procedures still follow empirical methods, therefore this study applied AASHTOWare Pavement ME Design (Version 2.3.1) software to identify the effects of design parameters on concrete overlay service life. The theoretical insights provided by Pavement ME Design were compared with historical performance data and used to provide recommendations with respect to optimized joint spacing in overlay pavement structures. Comparison of the historical performance-related data with Pavement ME Design software results indicates that the Pavement ME Design software is conservative in predicting concrete overlay service life.

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4.2 Introduction

Concrete overlay technology represents a pavement rehabilitation strategy to extend existing pavement service life when there is structural or functional inadequacy (Gross et al., 2017; Tores, Roesler, Rasmussen, & Harrington, 2012). Concrete overlays can provide an additional 15 to 40 years of service life to low or high-volume roads. Concrete overlays have been selected by local agencies in Iowa and around the country because of their ability to extend the life of an existing pavement cost effectively compared to other available techniques.

Concrete overlay types include bonded concrete-on-concrete (BCOC), unbonded concrete-on-concrete (UBCOC), bonded concrete-on-asphalt (BCOA), and unbonded concrete-on-asphalt (UBCOA). Although concrete overlay technology is not new, most design procedures still follow the 1993 AASHTO Guide for Design of Pavement Structures. However, this guide is based on empirical methods derived from road test results conducted on a single location in Ottawa, Illinois about 60 years ago (Tores et al., 2012), and cannot provide pavement performance predictions for different pavement structural design alternatives (i.e., overlay thickness, joint spacing and existing pavement performance).

In Iowa, many concrete overlay design procedures use such an empirical method. The most common joint spacing size adopted by Iowa agencies for concrete overlays are 3.7 m. × 3.7 m. (12 ft. × 12 ft.), and the thickness is usually greater than 152-mm. (6 in.). However, there are some concrete overlays with lower thicknesses (< 152-mm. (6 in.)) and greater joint spacing (> 3.7 m. (12 ft.)), some of which have exhibited poor performance. Since improper design and construction practices may result in premature failures for concrete overlays, it is desirable to address deficiencies in current concrete overlay design and construction practices.

To achieve long-lasting concrete overlay performance through proper design and construction practices, it is critical to understand actual concrete pavement performance behavior and identify design and construction-related factors that can result in either substandard or adequate performance of Iowa concrete overlay types. To address such questions, this study used two different approaches to evaluate the performance of concrete overlays built in Iowa, i.e., detailed reviews of Iowa concrete overlay historical performance data and analytical investigations using AASHTOWare Pavement ME Design (Version 2.3.1) software.

A review of concrete overlay performance data was conducted to identify occurrences of both adequate and substandard performance. Causes and impacts of such cases on concrete overlay service life estimations were also analyzed. In addition, the effects of structural design alternatives on concrete overlay performance have been identified using the latest version of AASHTOWare Pavement ME Design (Version 2.3.1). The findings were used to provide theoretical insights and assist in developing recommendations with respect to optimized joint spacing and overlay thickness. The procedures used, and the results of the analysis are discussed in this paper and the findings regarding improving long-term performance of concrete overlays are highlighted.

4.3 Methodology

4.3.1. Reviews of Iowa Concrete Overlay Historical Performance Data

Data used for the analyses were collected from the Iowa Pavement Management Program (IPMP). The automatic road analyzer (ARAN) used by the program to collect concrete overlay pavement condition data on all paved secondary roads since 2002. The data provided was an average for a given section that could vary in pavement section length. One PCC overlay construction project section represents one construction project. The properties recorded include transverse cracking, longitudinal cracking, faulting, D-cracking, joint spalling, and international roughness index (IRI). The Institute for Transportation (InTrans) manages the pavement condition data as part of the IPMP.

Concrete overlay performance data were reviewed in this study by analyzing International Roughness Index (IRI) measurements and a Pavement Condition Index (PCI) calculated from structural distress type measurements (i.e., transverse cracking and joint spalling), durability-related distress type measurements (i.e., D-cracking), and functional performance measurements (i.e., IRI). The PCI was calculated using Equation 1 which was derived based on the experience of local agencies over time (Gross et al., 2017).

For illustration, Figure 4-1 presents surface condition on concrete overlay road in Pottawattamie county where 77 of PCI and 2.3 m/km (147 in/mile) of IRI have been reported in year 2014. After reviewing the concrete overlay performance data, cases representing both adequate and substandard performance history were identified in terms of PCI and IRI history plots.

Figure 4-1 *Surface condition on concrete overlay road in Pottawattamie County, Iowa*

4.3.2. Analytical Investigations Using Pavement ME Design

AASHTOWare Pavement ME Design (Version 2.3.1) has implemented a concrete overlay design tool developed at the University of Pittsburgh (Li, Dufalla, Mu, & Vandenbossche, 2016) to predict concrete overlay performance and identify concrete overlay structural design alternatives for rehabilitation of existing pavement structures (Bhattacharya, Gotlif, & Darter, 2017).

This software supports a minimum longitudinal joint spacing of 3.7 m. (12 ft.) (full lane width), and a minimum transverse joint spacing of 3 m. (10 ft.) as design parameters. For this study, Des Moines was chosen as the climate station city, and the Annual Average Daily Truck Traffic (AADTT) number was taken as 75 noting that 82% of Iowa concrete overlay projects have an average daily traffic (ADT) range below 1,500 (see Table 4-1) and most of these projects are on the county road system. Considering that 2.5% to 10% of truck traffic is typical on Iowa county roads, this study selected 5% of truck traffic to calculate 75 of AADTT (= 1,500 of ADT × 5%).

Table 4-1 Distribution of Iowa Concrete Overlay Projects Average Daily Traffic (ADT)

ADT (count)	Percent of data based on number of projects (%)
<500	32
501-1,000	34
1,001-1,500	16
1,501-2,000	5
2,001-3,000	5
3,001-4,000	2
4,001-10,000	4
>10,000	2
Total	100

Three typical overlay structures were selected: bonded concrete-on-asphalt (BCOA), unbonded concrete-on-asphalt (UBCOA), and unbonded concrete-on-concrete (UBCOC). Table 4-2 presents the structural design parameters of these concrete overlay types used. The transverse joint spacing evaluated in this study were 3.7-m. (12 ft.), 4.5-m. (15 ft.) and 6.1-m. (20 ft.), while the longitudinal joint spacing was fixed at 3.7-m. (12 ft.) (i.e., full lane width).

While pavement ME Design local calibration studies (Ceylan, Kim, Gopalakrishnan, & Ma, 2013; Kaya, 2015; Kim, Ceylan, Ma, & Gopalakrishnan, 2014) previously conducted on the Iowa pavement system covers new jointed plain concrete pavements (JPCP) as rigid pavements, new hot mix asphalt pavements as flexible pavements, and HMA over JPCPs as composite pavements, no local calibration study on Iowa concrete overlay systems (either bonded or unbonded) has been previously conducted, therefore national calibrated performance prediction models were utilized in this study.

Table 4-2 Structural Design Parameters of Pavement ME Design on Iowa Concrete Overlays Projects

Design parameters	BCOA	UBCOA	UBCOC
Traffic (AADTT)		75	
Climate station		Des Moines	
Concrete overlay slab size: longitudinal joint × joint spacing (m.)	3.7 × 3.7 3.7 × 4.5 3.7 × 6.1	3.7 × 3.7 3.7 × 4.5 3.7 × 6.1	3.7 × 3.7 3.7 × 4.5 3.7 × 6.1
Thickness (mm.)	127 and 152	178 and 203	127, 152, 178 and 203
Existing AC/PCC layer thickness (mm.)	102 and 152	102 and 152	102 and 152
Interlayer thickness (mm.)	N/A	N/A	25

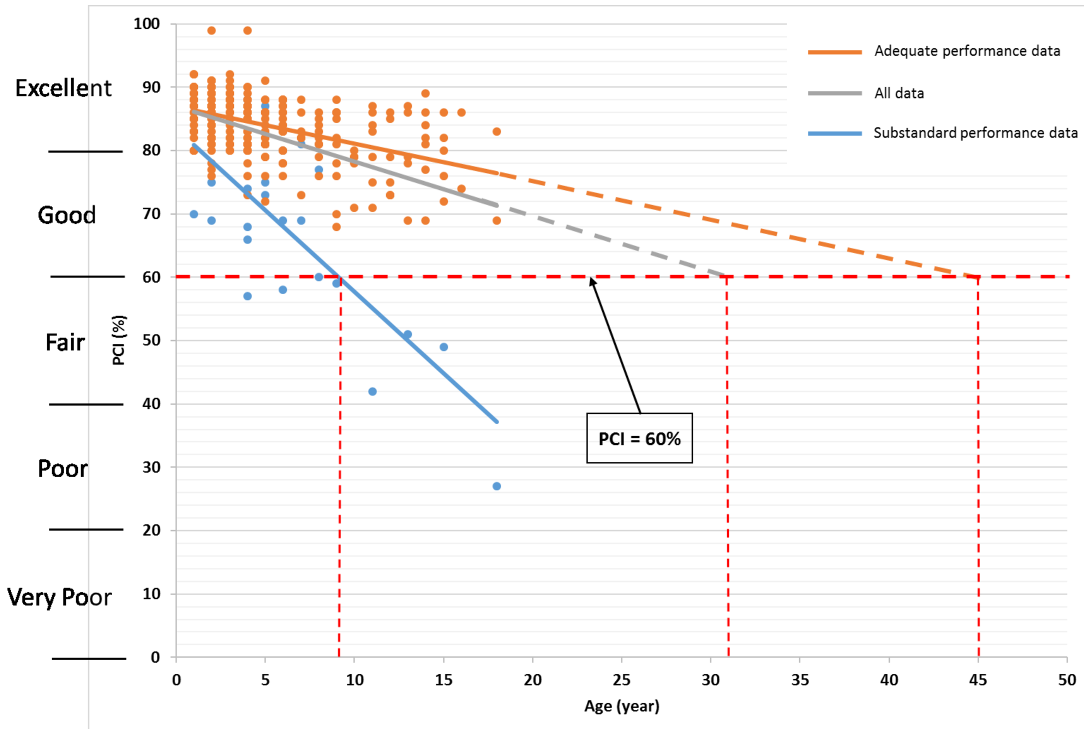
4.4 Result and Discussion

4.4.1. 3.7-Meter (12-Foot) Joint Spacing

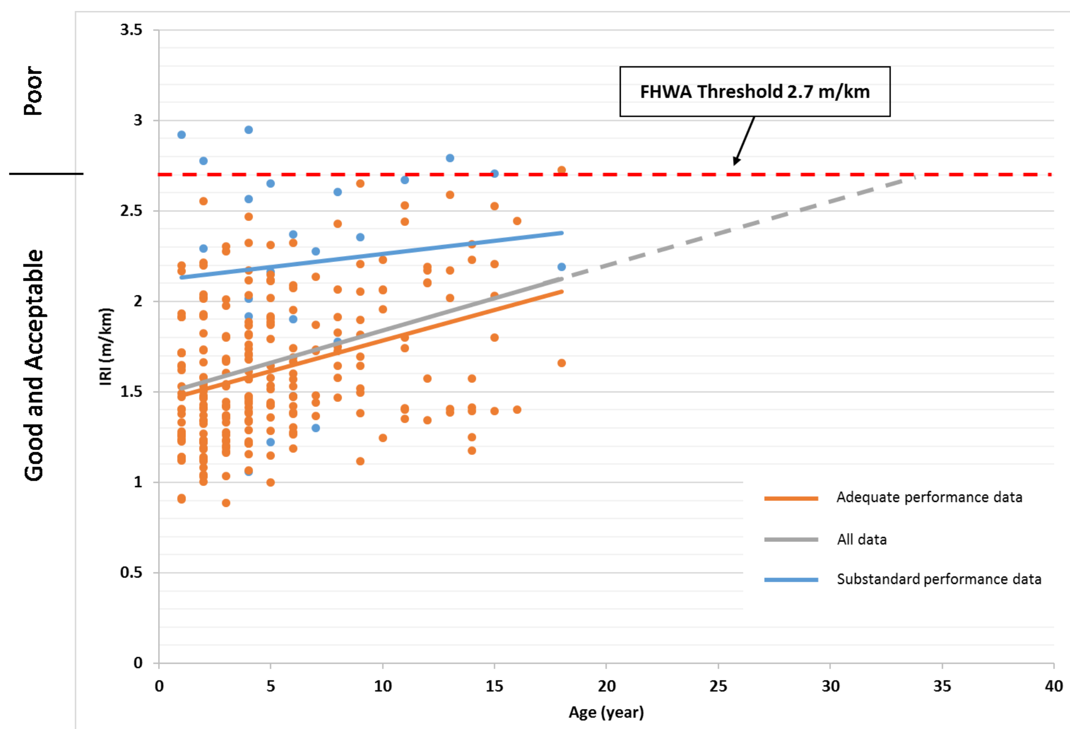
Figure 4-2 shows that both PCI and IRI change with age for 3.7-m. (12-ft.) joint spacing for data representing twenty years of service. There are total 113 projects represented in Figure 4-2, and each project may be reported at more than one age. The relationships between concrete overlay age and PCI and IRI values for each project are shown in Figure 4-2. It can be easily seen that PCI values have a slight downward trend as age increases, and IRI values have a slight upward trend as age increases. PCI and IRI values fall into two apparent categories that have been labelled as adequate, and substandard performance. Adequate performance typically reflected PCI values greater than 60% during the first 10 years of service, while substandard performance indicated a PCI value lower than 60% at 10 years. All data points, regardless of age, from a substandard section were labelled as such. Seven of the 113 projects appear to be performing in a substandard manner.

In Figure 4-2a, a best fit line for the complete data set shows PCI values that were greater than 60% for 31 years. If the “adequate performance” data set alone is projected out, an average life of 45 years can be expected, indicating that an extra 15 years can be expected on average if the causes of the premature failures can be prevented. The data set is noisy, and the correlation coefficients are poor, but the trends appear to be valid.

IRI values lower than 2.7 m/km (170 in/mile) are recommended as an acceptable performance threshold (Arhin, Noel, & Ribbiso, 2015). Similar to the PCI plots, IRI predictions (Figure 4-2b) indicate serviceability failure after just over 30 years. The IRI values of the substandard performance set appear to be initially high, likely due to poor construction practices.



(a)



(b)

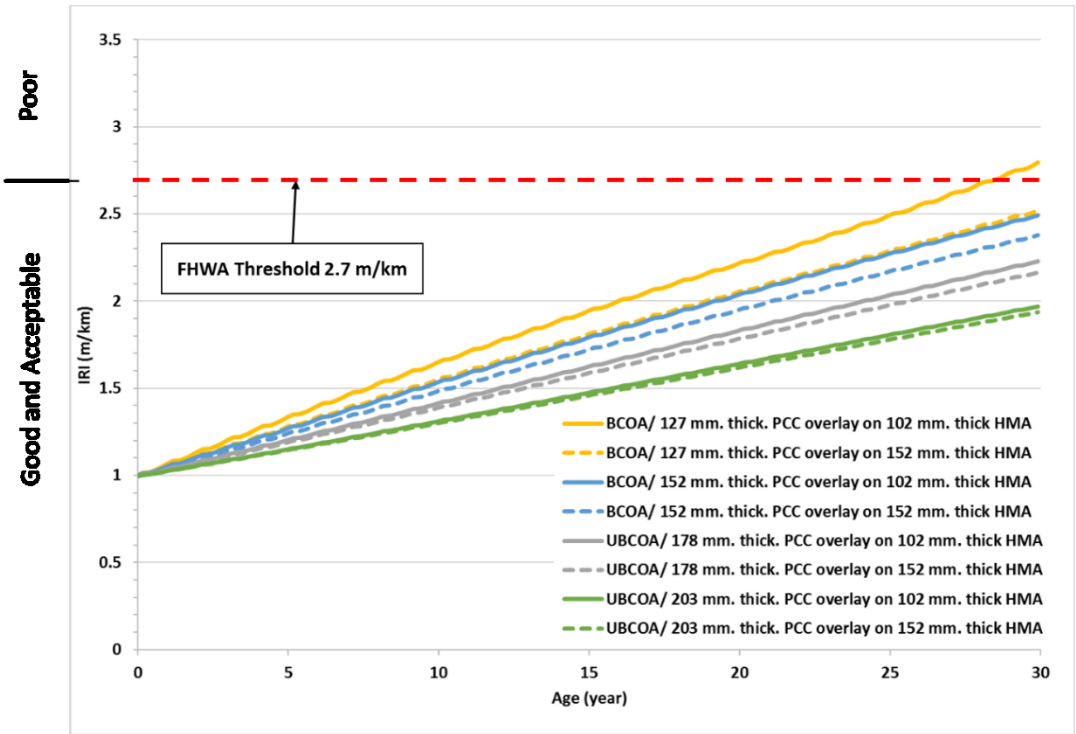
Figure 4-2 *3.7-meter (12-foot) joint spacing concrete overlays improved observed performance (a) PCI (b) IRI*

Figure 4-3 shows IRI values associated with increased pavement age for 3.7-m. (12-ft.) joint spacing based on the results produced by Pavement ME Design, indicating that a 30-year design life can be expected with 50% reliability (Ceylan, Coree, & Gopalakrishnan, 2008, 2009; Coree, Ceylan, & Harrington, 2005).

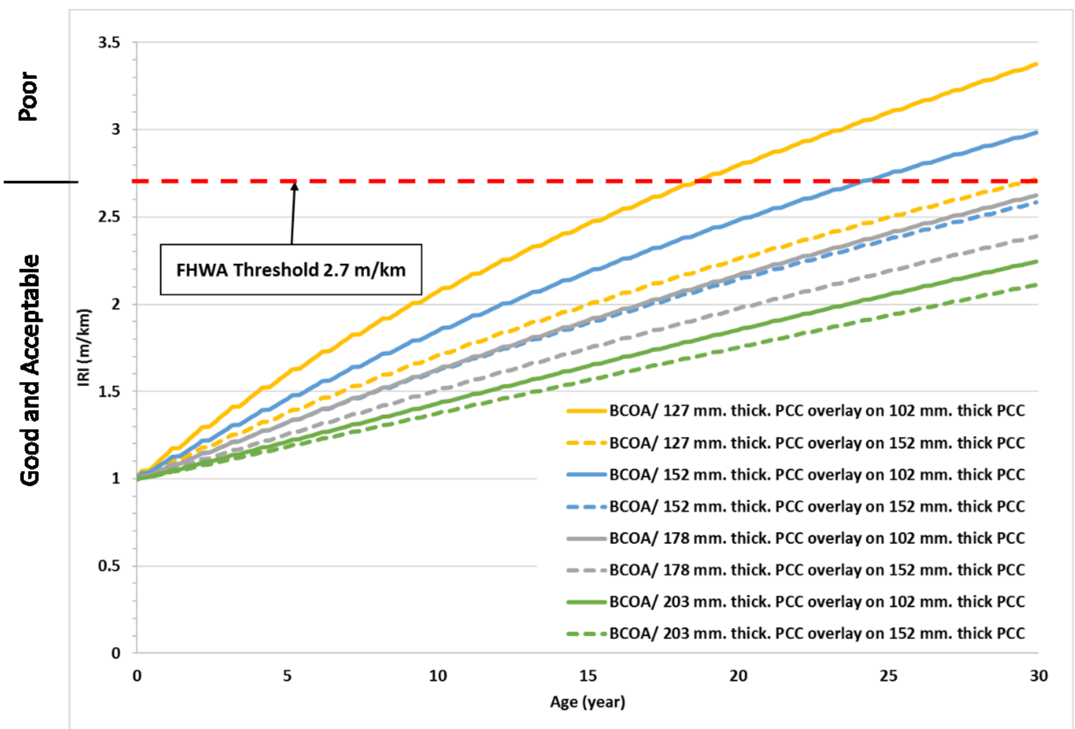
The existing pavement under an overlay should behave as a stable base with adequate load-carrying capability (Tores et al., 2012), so the existing pavement thickness and condition may be critical in affecting concrete overlay service life. Figure 4-3a summarizes results for bonded or unbonded concrete over asphalt pavement. It can be observed that, the thicker the PCC overlay, the longer the resulting service life. Thicker existing asphalt pavements (from 102-mm. (4-in.) to 152-mm. (6-in.)) may also extend service life for an overlay thickness less than 178-mm. (7-in.) although the benefit is reduced for thicker overlays.

Increased thickness of a UBCOC structure from 127-mm. (5-in.) to 203-mm. (8 in.) may result in extending service life from approximately 17 years to in excess of 30 years (Figure 4-3b).

The IRI performance data for 3.7-m (12-ft.) joint spacing predicted a service life of approximately 33 years (see Figure 4-3b) while the Pavement ME Design predictions ranged from 17 to in excess of 30 years (see Figure 4-3a and Figure 4-3b).



(a)

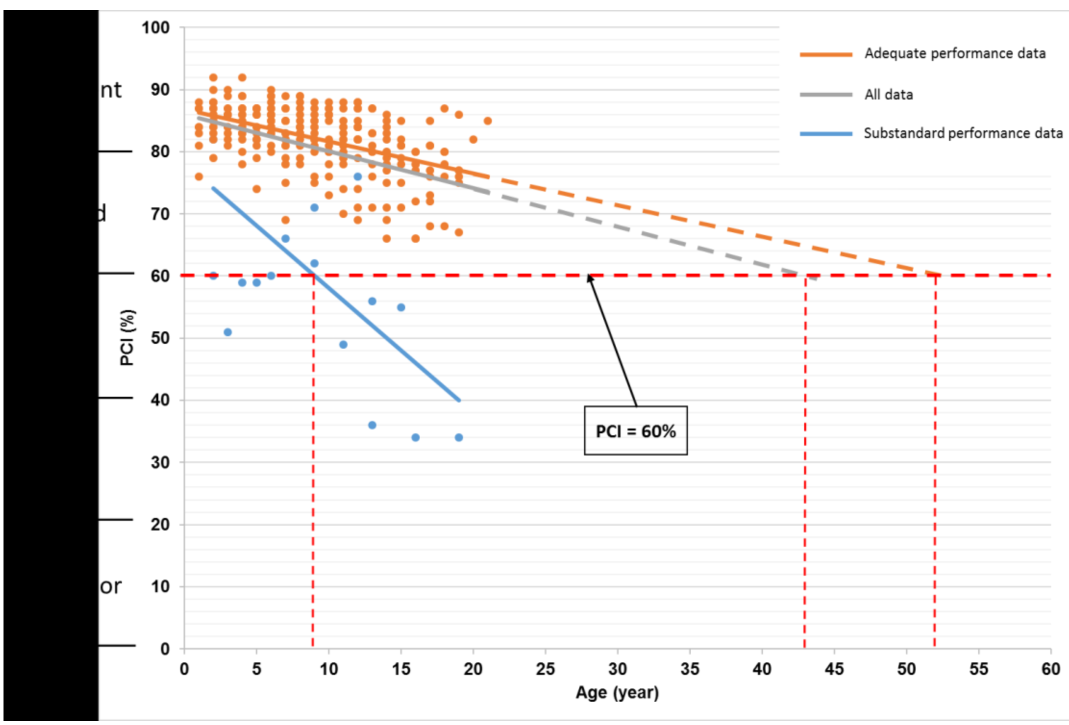


(b)

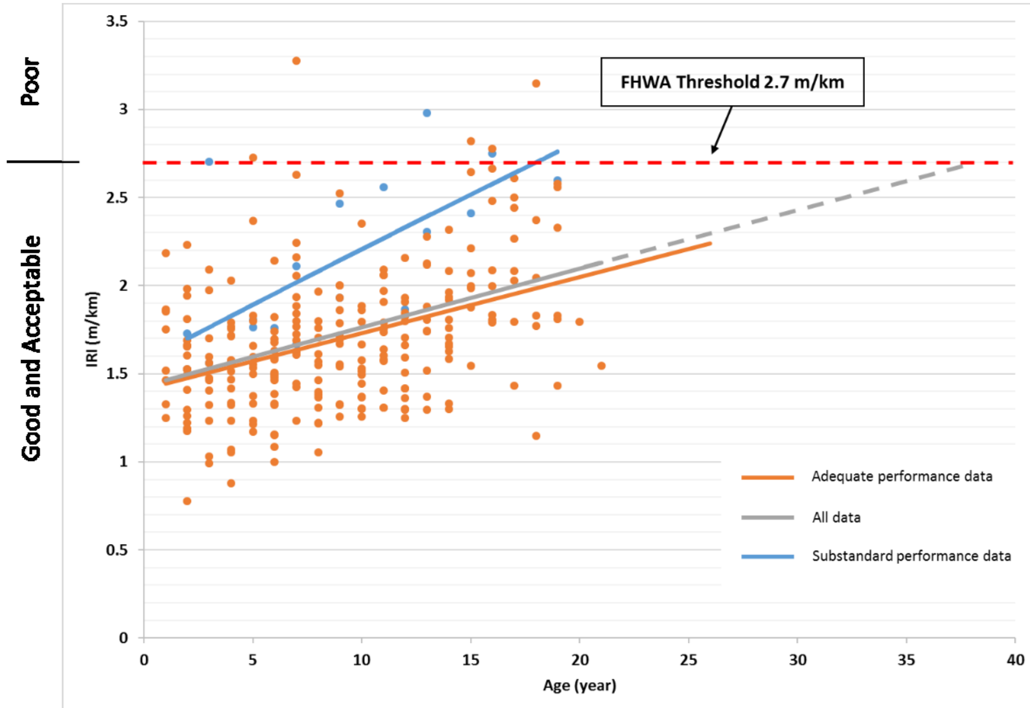
Figure 4-3 *3.7-meter (12-foot) joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: (a) BCOA, and UBCOA (b) UBCOC*

4.4.2. 4.5-Meter (15-Foot) Joint Spacing

Figure 4-4 depicts PCI and IRI changes with age for 4.5-m. (15-ft.) joint spacing, representing 74 projects in 266 data points. Figure 4-4a identifies both adequate (69 projects, 247 data points) and substandard performance data (5 projects, 19 data points). Fewer substandard performance data points are observed compared to that for the 3.7-m. (12-ft.) joint spacing overlays in Figure 4-2a. The longer 4.5-m. (15-ft.) joint spacing are typically associated with thicker overlays, potentially contributing to longer life. The trend line extended through the PCI values shown in Figure 4-4a indicates that overlays have the potential to last up to 42 years. If substandard performance data are excluded, the service life increases to about 52 years. IRI data (Figure 4-4b) indicates similar trends.



(a)



(b)

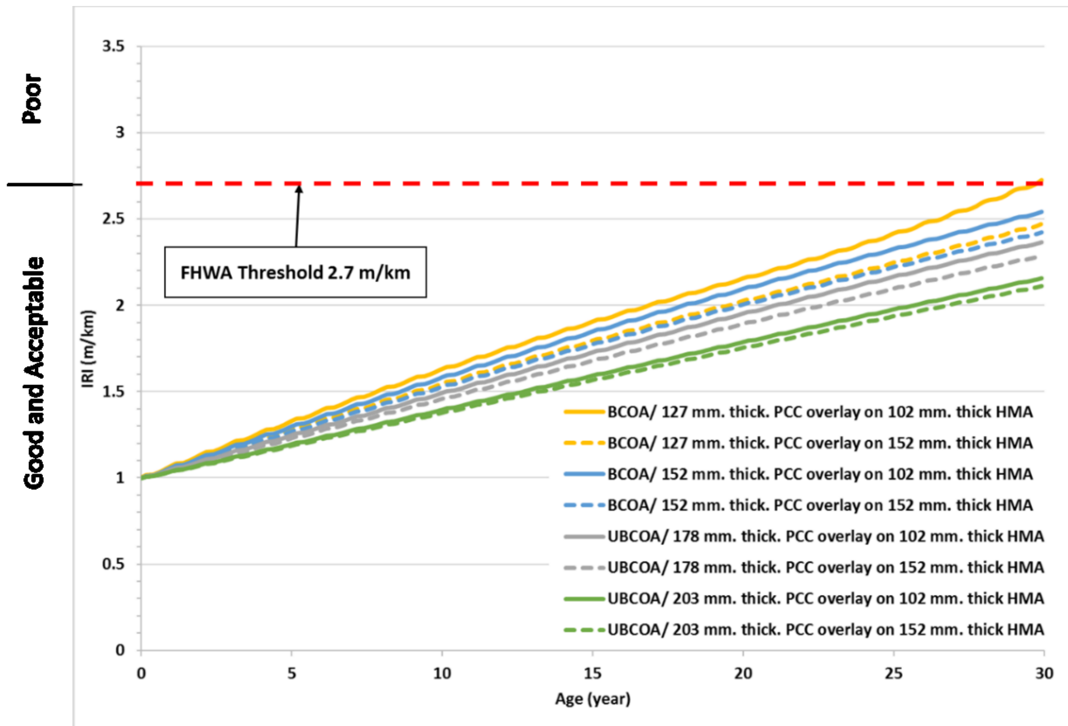
Figure 4-4 *4.5-meter (15-foot) joint spacing concrete overlays improved observed performance (a) PCI (b) IRI*

Figure 4-5 shows how IRI values change with age for 4.5-m. (15-ft.) joints based on the results obtained from the Pavement ME Design software.

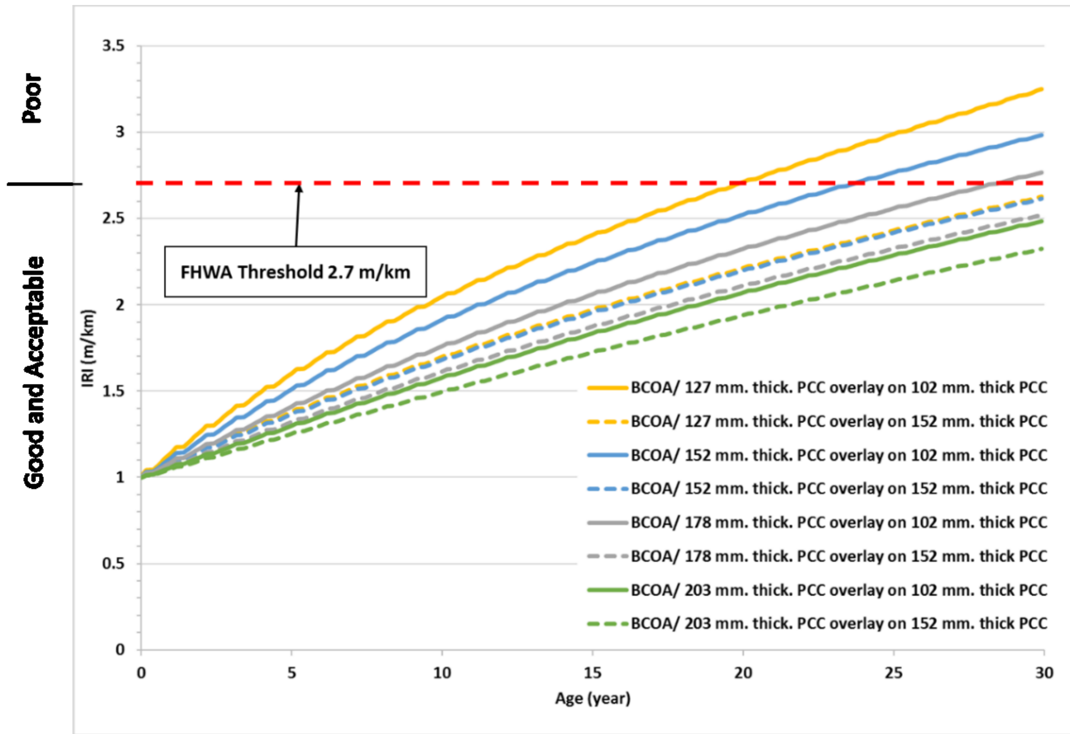
Figure 4-5a reflects use of asphalt pavement as the existing pavement. Similarly to Figure 4-3a, the thicker the PCC overlays, the longer the service life. While increasing thickness of existing asphalt pavements may extend concrete overlay service life. When overlays thickness is 203-mm. (8-in.), the predicted IRI value seems to be un-related to thickness of the existing asphalt pavement. However, as shown in Figure 4-5b, the service life of concrete overlays with a UBCOC structure can be extended by as much as 10 years with a thicker existing concrete pavement.

Comparing Figure 4-5a and b, PCC overlay structures of up to 203-mm. (8 in.) on a thicker existing asphalt pavement seems to take longer to reach the IRI threshold than for a thicker existing concrete pavement. In comparing Figure 4-3 and Figure 4-5, increased joint spacing to a 4.5-m. (15-ft.) design may result in a shorter service. It is possible that longer joint spacing would tend to reduce the efficiency of load transfer.

The historical performance data indicate longer life than that predicted by Pavement ME Design software.



(a)



(b)

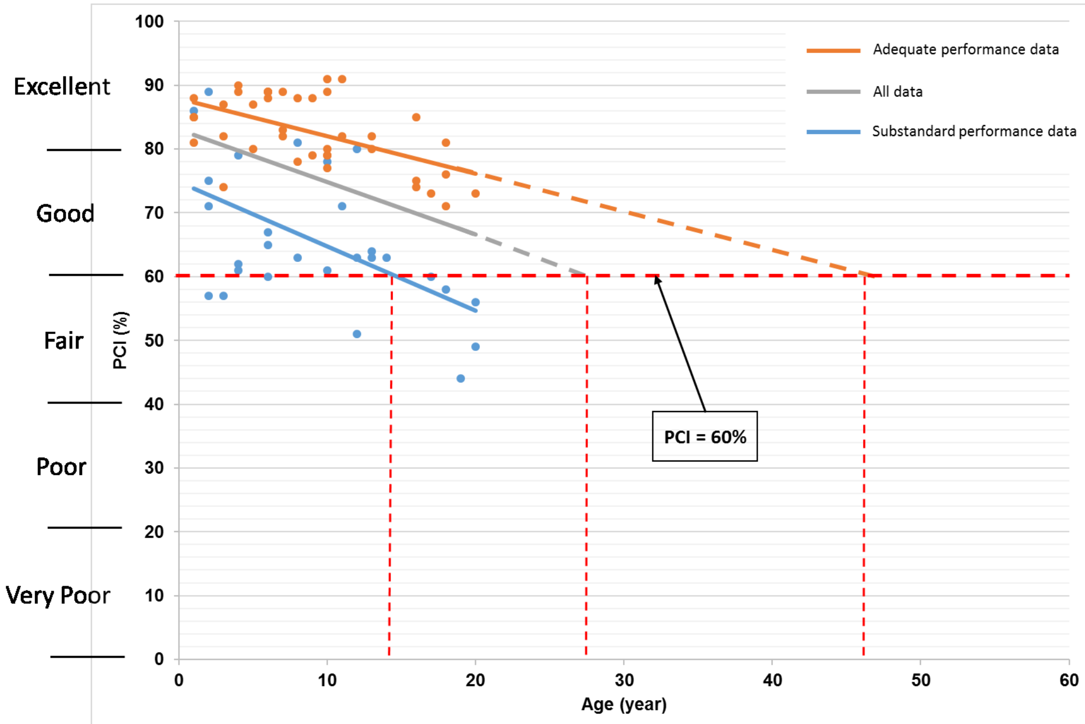
Figure 4-5 *4.5-meter (15-foot) joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: (a) BCOA, and UBCOA (b) UBCOC*

4.4.3. 6.1-Meter (20-Foot) Joint Spacing

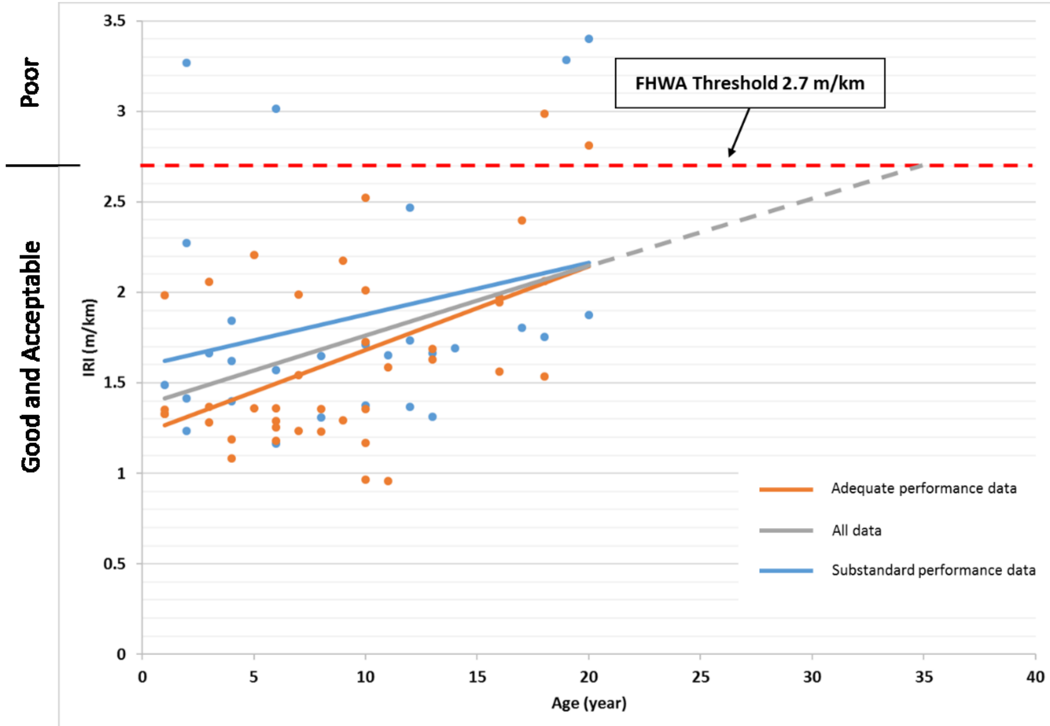
Figure 4-6 depicts how PCI and IRI change with age for 6.1-m. (20-ft.) joint spacing in 22 projects (68 data points). As for the other joint spacing, reducing premature failures could add to about 20 years of service life in terms of PCI values. In this case, nearly 50% of datasets lie in the substandard performance category (7 projects, 28 data points), possibly because 6.1-m. (20-ft.) joint spacing is just too long for concrete overlay design.

Compared to 3.7-m. (12-ft.) and 4.5-m. (15-ft.) spacing data sets, 6.1-m. (20-ft.) joint spacing data sets showed lower PCI values. Therefore, as previously discussed, the lower PCI values may have been caused by longer joint spacing combined with thinner overlays.

Figure 4-6b presents the 6.1-m. (20-ft.) joint spacing data sets of IRI values that did not exhibit a clear division. However, the substandard performance trend line had higher initial IRI values than for the adequate performance dataset.



(a)



(b)

Figure 4-6 *6.1-meter (20-foot) joint spacing concrete overlays improved observed performance (a) PCI (b) IRI*

Figure 4-7 shows how modeled IRI values change with age for 6.1-m. (20-ft.) joint spacing based on the results obtained from Pavement ME Design software.

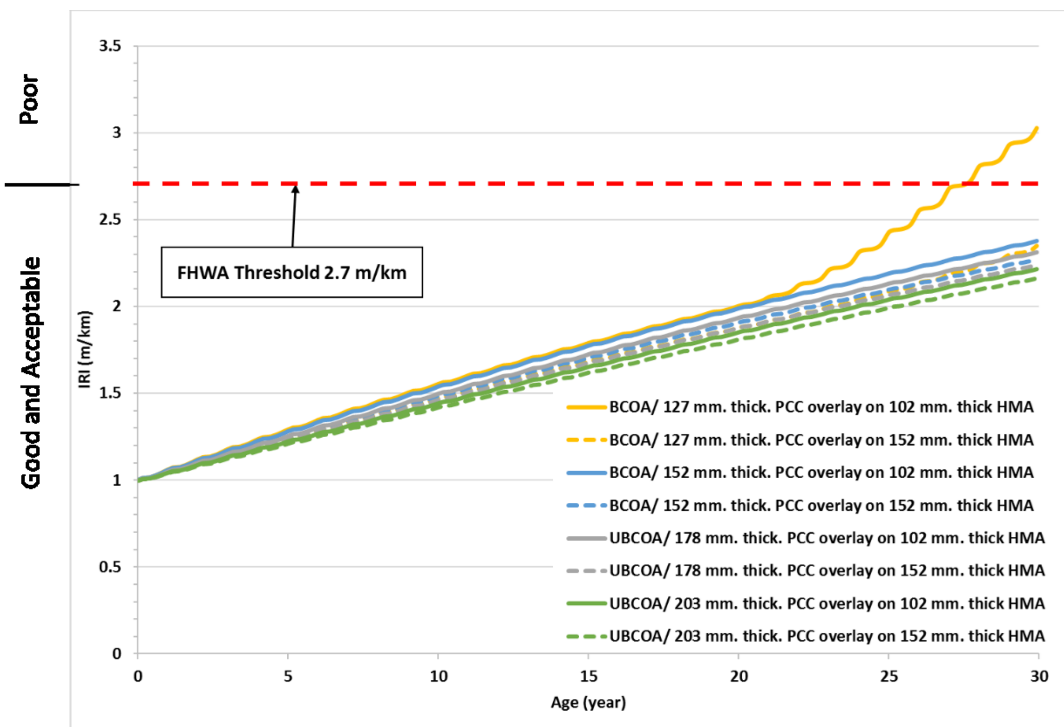
As shown in Figure 4-7a, thicker existing asphalt pavements could extend concrete overlay service life. However, increasing overlay thickness has little effect on IRI, probably because 6.1-m. (20-ft.) joint spacing is a too long for use in concrete overlays.

A rule of thumb is that for 127-mm. (5-in.) to 178-mm. (7-in.) thick slabs, the maximum transverse joint spacing design is 24 times the thickness up to a maximum of 4.5-m. (15-ft.) (Harrington & Fick, 2014). Therefore, for joint spacing of 6.1-m. (20-ft.), the thickness of both existing pavement layer and overlays seems to have small impact on IRI. Similar to the behavior shown in Figure 4-7b, increasing the thickness of a UBCOC structure from 127-mm. (5-in.) to

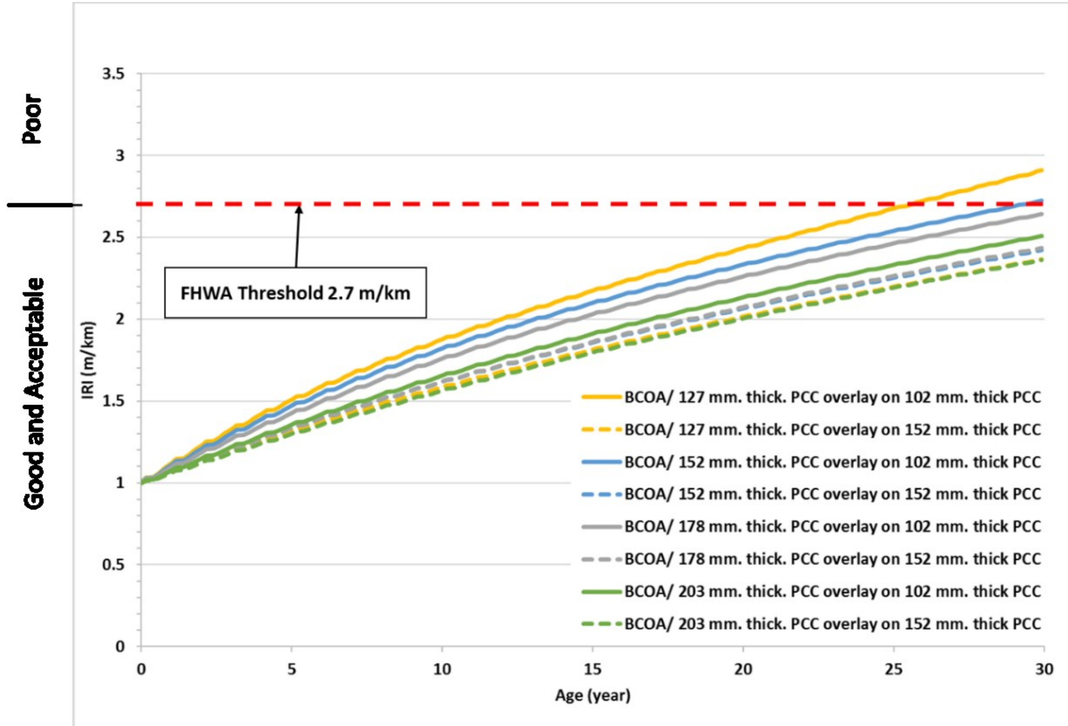
152-mm. (6-in.) may result in extending service life by only approximately 5 years before reaching the IRI performance limit.

These observations indicate that, like the results for 3.7-m. (12-ft.) and 4.5-m. (15-ft.) joint spacing overlays, a thicker existing pavement layer and thicker PCC overlay pavement would be expected to extend service life. Based on the BCOA and UBCOA results, when the overlay thickness is greater than 152-mm. (6-in.), the maximum service life exceeds 30 years. Compared with 3.7-m. (12-ft.) and 4.5-m. (15-ft.) joint spacing results, the 6.1-m. (20-ft.) joint would have a shorter service life when the overlay thickness is 127-mm (5-in.).

Comparison of the historical performance-related data with Pavement ME Design software results indicate similar values.



(a)



(b)

Figure 4-7 *6.1-meter (20-foot) joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: (a) BCOA, and UBCOA (b) UBCOC*

4.5 Conclusions

This study evaluated the performance of concrete overlays built in Iowa over the last 20 years. PCI history plots indicate that overlay service life can be extended by ensuring that premature failure mechanisms are avoided.

AASHTOWare Pavement ME Design (Version 2.3.1) was also used to identify effects of joint spacing and thickness on concrete overlay service life. The major findings can be summarized as follows:

- IRI values showed that higher overlay thickness leads to increased overlay service life.
- Increasing existing pavement thickness, leads to extension of overlay service life, depending on the design of the overlay.

- When the PCC overlays is less than 178-mm. (7-in.) thick, 3.7-m. (12-ft.) joint spacing overlays have similar service life to that of a 6.1-m. (20-ft.) joint spacing. When the overlay thickness is greater than 178-mm. (7-in.), a shorter joint spacing appears to be preferred.
- Comparison of the historical performance-related data with Pavement ME Design software results indicates that the Pavement ME Design software is conservative in predicting concrete overlay service life.

4.6 Acknowledgements

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CHAPTER 5. IOWA CONCRETE OVERLAY PERFORMANCE PREDICTION EVALUATION USING ARTIFICAL NEURAL NETWORKS

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5.1 Abstract

Prediction of future pavement performance of a road network is important in pavement management systems (PMS). A major goal of PMS is to identify cost-effective resource-allocation strategies for extending pavement service life. Although many pavement performance prediction models have been developed during over the years, a concrete overlay performance prediction model has not been developed in Iowa, making a prediction model for Iowa concrete overlay performance most desirable. Developing a comprehensive overlays performance prediction model is challenging, because an accurate pavement performance prediction model depends greatly on a number of parameters, such as condition data, local traffic, and environmental condition data. Iowa has a comprehensive concrete overlay database that records the historical performance of concrete overlays, including the International Roughness Index (IRI), an important parameter in evaluating concrete overlay ride quality and long-term performance. In this paper, ANN-based models used four different groups of input variables: distress data, construction design data, traffic data, and climate data, to predict IRI values. This study developed an overlay pavement performance prediction model in Iowa, with results reflecting a root-mean-squared error (RMSE) less than 10% of the range of IRI values. Results

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from the ANN model prediction indicate that using only construction design and traffic data variables only can produced practical analysis predictions for Iowa.

5.2 Introduction

Use of Concrete overlays represents a common pavement maintenance and rehabilitation strategy used to extend existing pavement service life in situations where existing pavements exhibit structural or functional inadequacy (Gross, et al., 2017; Tores, Roesler, Rasmussen, & Harrington, 2012). Condition of concrete overlay pavements has been assessed using several different condition indices. In this study, performance of one type of concrete overlay was analyzed in terms of International Roughness Index (IRI) values. IRI measurement, introduced in the 1980s (Sayers, Gillespie, & Paterson, 1986; Sayers, Gillespie, & Queiroz, 1986), has become one of the primary indicators used to assess road conditions because it results in correlation between vehicle vibration level and pavement-loading vibration level. Iowa concrete overlay IRI recorded in the concrete overlay pavement performance data were collected by a vendor using an automatic road analyzer (ARAN).

Prediction of future pavement performance of a road network is a significantly for pavement management systems (PMS), because reliably predicted performance supports cost-effective rehabilitation and maintenance strategy that can then be used to extend pavement service life (Roberts & Attoh-Okine, 1998; Terzi, 2007). An appropriate pavement performance prediction model can also be used to reduce the amount of required data-collection costs (Roberts & Attoh-Okine, 1998). Success of a pavement performance prediction model greatly depends on parameters such as condition data, local traffic, and environmental condition data. Iowa Pavement Management Program (IPMP) using an automatic road analyzer (ARAN) has collected such data for all paved secondary roads since 2002, so this paper had access to a pavement performance and local traffic database sufficient for determining accuracy of a concrete overlay prediction model.

There are several different machine-learning tools that can be used in analysis and prediction of pavement performance, and artificial neural networks (ANN) are one such type of machine learning tool. ANN models have been successfully used in various fields of application, especially in pavement design, analysis, and solving pavement engineering problems (Ceylan, Bayrak, & Gopalakrishnan, 2014; Kaya, et al., 2018; Rezaei-Tarahomi, et al., 2017). Compared with other statistical techniques, the ANN model has demonstrated higher accuracy on non-linear functions (Gardner & Dorling, 1998). Concrete overlay pavement performance is affected by several parameters (i.e., material properties, environmental condition, existing pavement condition, and traffic loading), and deterioration of ride quality is a non-linear function. Since the use of ANN-based models to predict pavement performance could potentially save significant amounts in data-collection time and budget for government agencies, and an ANN-based prediction model could provide decision makers with optimal strategies for extending pavement service life, this study applied an ANN model for prediction of pavement performance.

Pertinent literature has focused on how to use non-linear analysis for pavement performance to predict material and pavement serviceability (Panas, Pantouvakis, & Lambropoulos, 2012). In contrast to the material presented in this paper, the majority of previous studies have used only a small amounts of data in non-linear analyses or machine learning models, so this study's prediction models used the entire Iowa concrete overlay performance data set to generate a more realistic prediction model.

The main purpose of this paper is to develop and practical ANN model for predicting concrete overlay performance based on field data collection. The model uses four groups of input variables to predict the ride quality (i.e., the IRI value). These groups include distress data (i.e., transverse cracking, D-cracking, joint spalling, and faulting), construction design data (i.e., overlay type, overlay thickness, joint spacing, and age), traffic data, and climate data (i.e., temperature, wind speed, relative humidity, percentage sunshine, and precipitation).

5.3 Methodology

5.3.1. Database Development

To help in developing an appropriate database of input-output records from the IPMP database, 354 concrete overlay projects in Iowa were included in the study. Iowa concrete overlay performance data were obtained from a pavement distress data set maintained by the IPMP. The IPMP has maintained the data collected in the state system as well as in local systems since 1998. The collected concrete overlay pavement performance data includes transverse cracking, faulting, D-cracking, joint spalling and international roughness index (IRI), etc. This paper also used the modern retrospective analysis for research and applications (MERRA) collected by NASA's Global Modeling and Assimilation Office for climate-related inputs.

5.3.2. ANN Model Development

ANN models have previously been applied for prediction of pavement performance that is influenced by many different variables. In this study, three different case studies have been considered while investigating ANN model development using a variety of input variables, including overlay type, overlay thickness, joint spacing, traffic, age, transvers cracking, D-cracking, joint spalling, faulting, and climate data (i.e., temperature, wind speed, relative humidity, percentage sunshine, and precipitation). IRI values were the output variables. Training ANN models can be implemented using different architectures with different numbers of hidden layer. In this study, after testing more than 1,000 runs of ANN models with a variety of hidden neurons, and different numbers of hidden layers, it was found that one hidden layer exhibited greater accuracy than two hidden layers, so a single hidden layer was found sufficient for predicting concrete overlay performance in the MATLAB environment.

For developing ANN model and evaluating its accuracy, the whole data set (1,133 data values in total) was divided into four parts: 1. Training; 2. Testing; 3. Validation; and 4. Independent testing. Since independent testing data was randomly selected and separated before creating the ANN model, all the Independent testing data were the same for every ANN model. On the other hand, since testing data was randomly selected while creating the ANN model, testing data was different for each ANN model, even for each fold. Table 5-1 shows the sample numbers used in each part. The samples were randomly selected to reduce the chance that the data might be biased toward uncommon or extreme events. From the developed candidate models, those most accurately predicting independent test results were selected as the final models. During ANN model development, three types of network architectures were considered, each with a different number of input variables (Case 1 study – 14 input variables, Case 2 study – 9 input variables, and Case 3 study – 5 input variables). Each network architecture was examined in a MATLAB environment. Because of the possibility of reaching a local minimum of the performance surface, a single training run may not produce optimal performance, so restarting the training using several different initial conditions and selecting the network that produces the best performance can help to prevent falling into a local minimum. ANN models for each input case were trained 10 times and, among these 10 models, the one most accurately predicting (lowest RMSE or highest LOE R^2) independent test results was selected as the final model.

Table 5-1 Distribution of training, testing, validation, and independent testing data

ANN modeling steps	Number of patterns in sample
Training	700
Testing	150
Validation	150
Independent testing	133

In this study, six different backpropagation training algorithms were investigated: Resilient Backpropagation, Conjugate Gradient Backpropagation with Powell-Beale Restarts, Scaled Conjugate Gradient, BFGS Quasi-Newton, Levenberg-Marquardt, and Bayesian Regularization.

Resilient backpropagation (RP) used local gradient information to fit weight and bias values (Demuth & Beale, 2002). Powell-Beale Restarts backpropagation was one example of the conjugate gradient algorithm method. All conjugate gradient algorithms started by searching in the steepest descent direction (negative of the gradient) on the first iteration. A line search was then implemented to determine the optimal distance to move along the current search direction. In a Fletcher-Reeves update, a new search direction was determined by computing the ratio of the norm squared of the current gradient to the norm squared of the previous gradient (Rezaei-Tarahomi, Kaya, Ceylan, Kim, & Brill, 2018). This algorithm was useful for large-scale unconstrained optimization (Demuth & Beale, 2002; Gopalakrishnan, 2010; Rezaei-Tarahomi, Kaya, Ceylan, Kim, & Brill, 2018). To avoid time-consuming line searching used in conjugate gradient methods the scaled conjugate gradient backpropagation (SCG) was developed as a very efficient algorithm for large networks, because it avoids the line search steps and significantly reduces the number of computations required during each iteration (Demuth & Beale, 2002; Gopalakrishnan, 2010).

The BFGS algorithm was developed by Broyden, Fletcher, Goldfarb, and Shanno was a popular quasi-Newton algorithm. Although the BFGS algorithm often converges faster than in conjugate gradient methods, it was more complex and expensive for feedforward neural networks. BFGS could be an efficient training algorithm for smaller networks (Demuth & Beale, 2002; Gopalakrishnan, 2010). Levenberg-Marquardt (LM) backpropagation was the fastest backpropagation algorithm; it could solve non-linear least squares and curve-fitting problems and was efficient for training networks with a few hundred weights. Bayesian regularization (BR) backpropagation was another training algorithm that updates LM optimization weight and bias values and was also one of the best approaches for avoiding over-fitting tendencies of neural networks. The BR training algorithm enhanced prediction accuracies for independent and unseen data by minimizing a combination of squared errors and weights, and by determining the correct combination for producing a network that generalizes well (Demuth & Beale, 2002; Gopalakrishnan, 2010).

ANN model accuracies were quantified using statistical indices of line of equality coefficient of determination (LOE R^2) and root-mean-squared error (RMSE), as defined in

$$LOE\ R^2 = 1 - \frac{n-p}{n-1} \times \left(\frac{S_e}{S_y}\right)^2 \qquad \text{(Equation 5-1)}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{j=1}^{n}\left(y_j^{prediction} - y_j^{solution}\right)^2}{n}} \qquad \text{(Equation 5-2)}$$

where p = total number of explanatory variables in the model; n = number of data points in each IRI comparison; S_e = Standard error of the estimates; S_y = Standard deviation of the estimates; $y^{solution}$ = critical pavement response from IPMP IRI value; $y^{prediction}$ = the critical pavement response predicted by ANN models. Accurate prediction is associated with a high value of LOE R^2 and a low value of RMSE.

5.4 Results and Discussion

5.4.1. Case 1 Study – 14 Input Variables

Figure 5-1 presents the three-layer ANN network architecture used for developing the performance-prediction models. This architecture was selected after an investigation of several configurations using the root-mean-squared error (RMSE) between the predicted and field IRIs as the basis for selection. There are 14 different variables in the input layers, including distress data (i.e., transverse cracking, D-cracking, joint spalling, and faulting), construction design data (i.e., overlay type, overlay thickness, joint spacing, and age), traffic data, and climate data (i.e., annual average temperature (AAT), annual average wind speed (AAWS), annual average relative humidity (AARH), annual average percentage sunshine (AAPS), and annual average precipitation (AAP)).

The data are passed from the input layer to the single hidden layer, flexibly-sized from 10 to 100 neurons. 10 consecutive ANN models were developed in a MATLAB environment for each hidden-neuron case. Six different categories of training algorithms (i.e., Levenberg-Marquardt backpropagation, Bayesian regularization backpropagation, BFGS backpropagation, Resilient backpropagation, Scaled conjugate gradient backpropagation, and Powell-Beale Restarts backpropagation) were used. The outputs used in model development were IRI values collected from the IPMP database. The developed ANN model was used to predict concrete overlay IRI values.

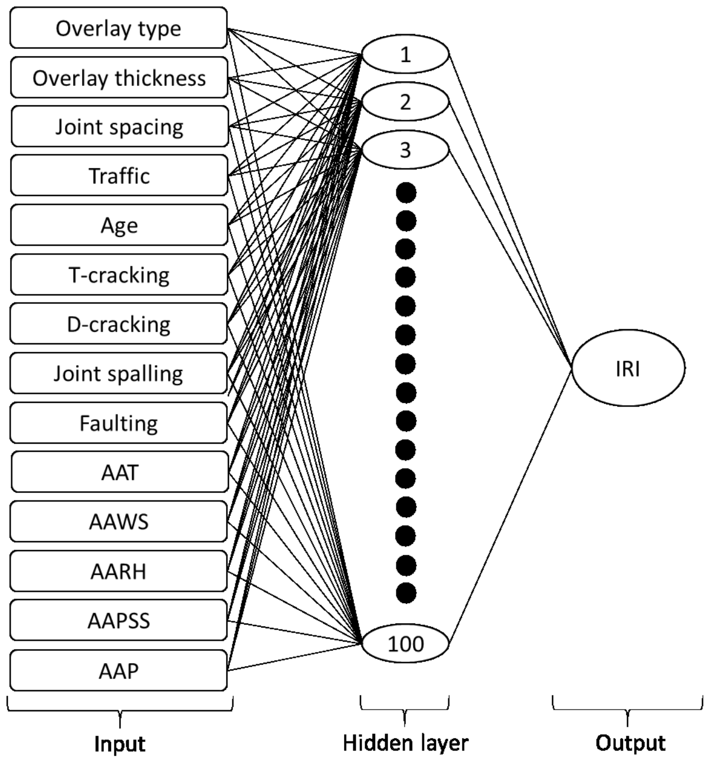


Figure 5-1 *ANN network architecture of case 1 study IRI values*

In this ANN model case 1 study, scaled conjugate gradient backpropagation was found to be the most optimal training algorithm, as shown in Table 5-2. In addition, the models developed with a hidden neuron size of 65 produced higher accuracy than other hidden neuron sizes. The LOE R2 values were 0.68 for training, 0.47 for testing, 0.24 for validation, and 0.37 for independent testing. The RMSE values were 0.26 m/km for training, 0.46 m/km for testing, 0.39 m/km for validation, and 0.34 m/km for independent testing. Figure 5-2 provides a concrete overlay pavement performance comparison between field measurements and the ANN model predictions from the optimal training algorithm. As can be seen in this figure, the predicted IRI values for training, testing, validation, and independent testing produced relatively small RMSE values and the predicted IRI values accumulated around the line of equality. Figure 5-3 presents an independent testing Q-Q (quantile-quantile) plot to compare two samples (field IRI and ANN model predictions with optimal training algorithm) of data to verify model assumptions. According to Figure 5-3, while some outliers (fewer than 10) are seen at the end of the range, it seems that the developed ANN model led to good correlation between predicted and-field-measured IRI values.

Table 5-2 Case 1 ANN model training algorithms accuracy (R^2 and RMSE)

Training algorithms	Training		Testing		Validation		Independent testing	
	R^2	RMSE (m/km)	R^2	RMSE (m/km)	R^2	RMSE (m/km)	R^2	RMSE (m/km)
Levenberg-Marquardt	0.60	0.30	0.43	0.40	0.29	0.35	0.34	0.42
Bayesian regularization	0.62	0.27	0.21	0.39	0.31	0.38	0.34	0.35
BFGS	0.49	0.30	0.25	0.42	0.26	0.37	0.34	0.33
Resilient	0.66	0.26	0.22	0.57	0.26	0.41	0.42	0.40
Scaled conjugate gradient	**0.68**	**0.26**	**0.47**	**0.46**	**0.24**	**0.39**	**0.37**	**0.34**
Powell-Beale Restarts	0.42	0.31	0.37	0.40	0.17	0.41	0.34	0.38

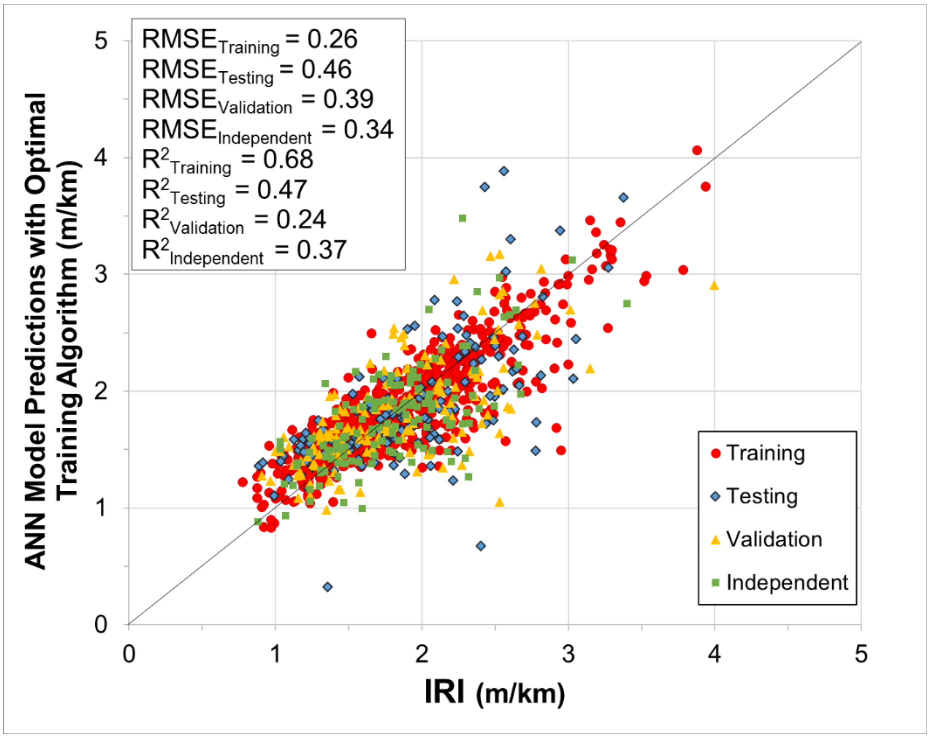


Figure 5-2 *Case 1 study field IRI values versus ANN model predictions with optimal training algorithm for training, testing, validation, and independent testing date sets*

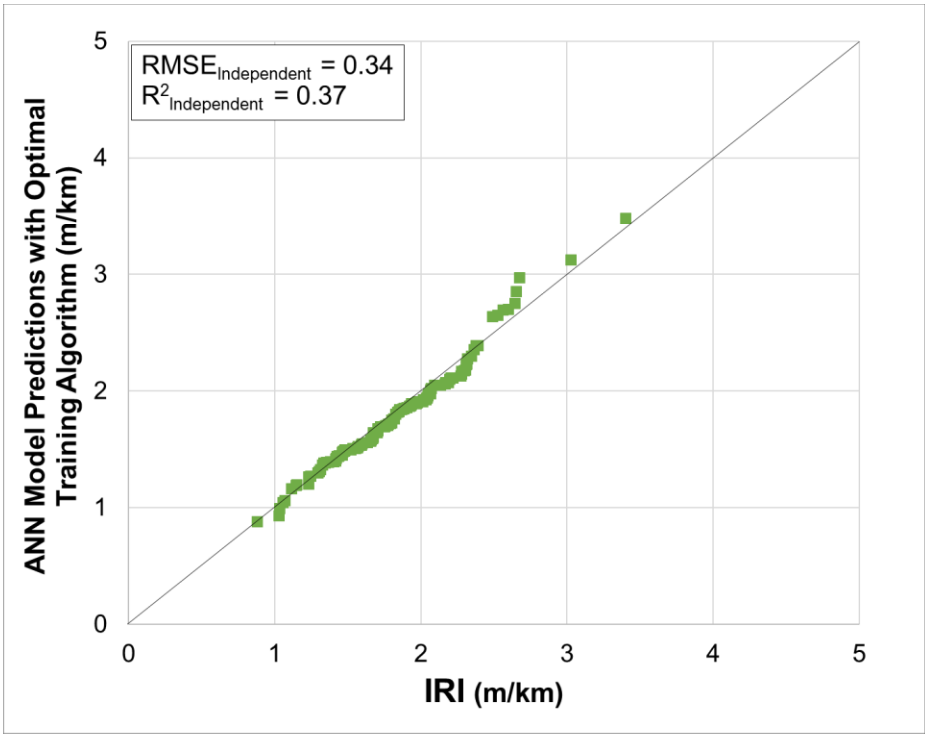


Figure 5-3 *Case 1 study field IRI values versus ANN model predictions with optimal training algorithm for independent testing data set*

5.4.2. Case 2 Study – 9 Input Variables

Figure 5-4 presents the ANN network architecture used in the model development. Compared to the case 1 study, in case 2 study climate data were eliminated, so the input layer had nine variables, including distress data, construction design data, and traffic data. In addition, using a single hidden layer with the number of hidden neurons varying from 10 to 100, ten consecutive ANN models were developed in the MATLAB environment for each hidden-neuron case. Six different training algorithms were used in the model development and one output layer was used in the ANN network architecture. This ANN model was developed for predicting concrete overlay IRI values. The main benefit resulting from elimination of climate data is that the ANN model can be developed using fewer input variables compared with case 1's study; there are only nine input variables in the case 2 study. Using fewer input variables reduced the amount of ANN model computing time and other resources.

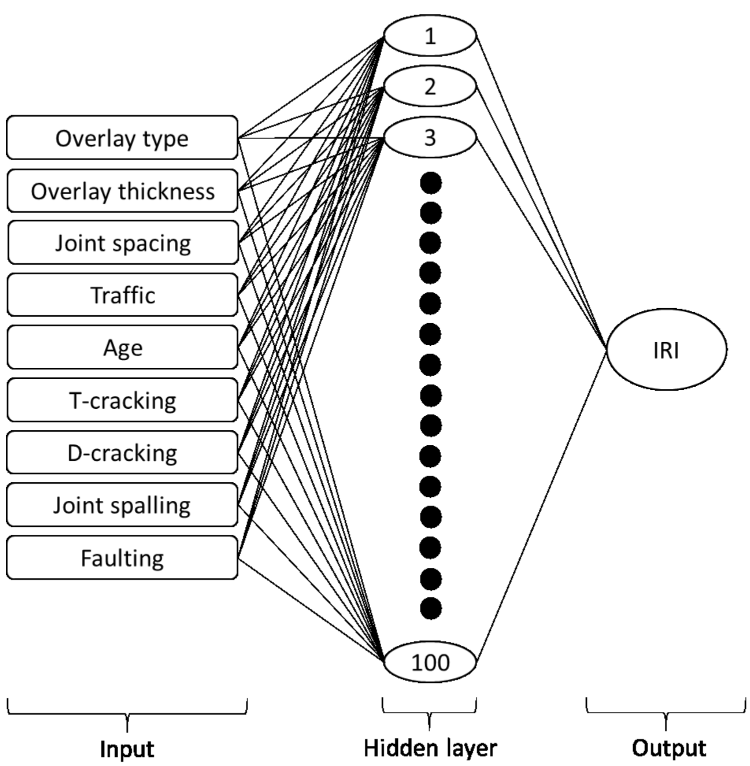


Figure 5-4 *ANN network architecture of case 2 study IRI values*

Based on the ANN model case 2 study, resilient backpropagation was found to be the most optimal training algorithm (see Table 5-3). In addition, the models developed with a hidden neuron size of 30 neurons produced higher accuracy than that with other numbers of hidden neuron sizes. The LOE R^2 values for ANN model results were 0.56 for training, 0.41 for testing, 0.49 for validation, and 0.45 for independent testing. The RMSE values were 0.27 m/km for training, 0.32 m/km for testing, 0.35 m/km for validation, and 0.31 m/km for independent testing.

A plot of field measurement IRI values versus ANN model predictions with optimal training algorithm with RMSE is shown in Figure 5-5. The independent testing prediction IRI values from the case 2 study ANN model at RMSE is 0.31 m/km (See Figure 5-5), compared with 0.34 m/km from the case 1 study ANN model (See Figure 5-2). The statistical values in the case 2 study had higher independent testing LOE R^2 values and lower RMSE values than those in the case 1 study. Although the case 1 study training dataset performed better than the case 2 study, since the RMSE would be reduced by an increasing number of training times, the final predicted IRI model provides better agreement between actual and field measurement IRI values. It seems that the climate data does not strongly affect Iowa concrete overlay pavement performance for two reasons: 1. this study used annual average climate data, because Iowa collected its performance data only once per year, making it difficult to identify climate variances. 2. Iowa topography is flatland, so the state climate does not have much variability. Figure 5-6 presents an independent testing Q-Q plot to compare two samples (field IRI and ANN model predictions with optimal training algorithm) of data to verify model assumptions. According to Figure 5-6, some outliers (fewer than 10) are present at the extreme ends of the range. Based on the independent testing Q-Q plot, the goodness of fit is high, and the independent testing RMSE value of 0.31 m/km indicates that an ANN model used for prediction IRI values is a valuable and practical analysis tool.

Table 5-3 Case 2 ANN model training algorithms accuracy (R^2 and RMSE)

Training algorithms	Training		Testing		Validation		Independent testing	
	R^2	RMSE (m/km)	R^2	RMSE (m/km)	R^2	RMSE (m/km)	R^2	RMSE (m/km)
Levenberg-Marquardt	0.58	0.27	0.31	0.49	0.25	0.60	0.43	0.40
Bayesian regularization	0.57	0.27	0.32	0.36	0.38	0.36	0.37	0.32
BFGS	0.35	0.32	0.24	0.34	0.06	0.30	0.26	0.33
Resilient	**0.56**	**0.27**	**0.41**	**0.32**	**0.49**	**0.35**	**0.45**	**0.31**
Scaled conjugate gradient	0.71	0.24	0.06	0.41	0.10	0.40	0.46	0.32
Powell-Beale Restarts	0.69	0.24	0.46	0.39	0.14	0.77	0.44	0.35

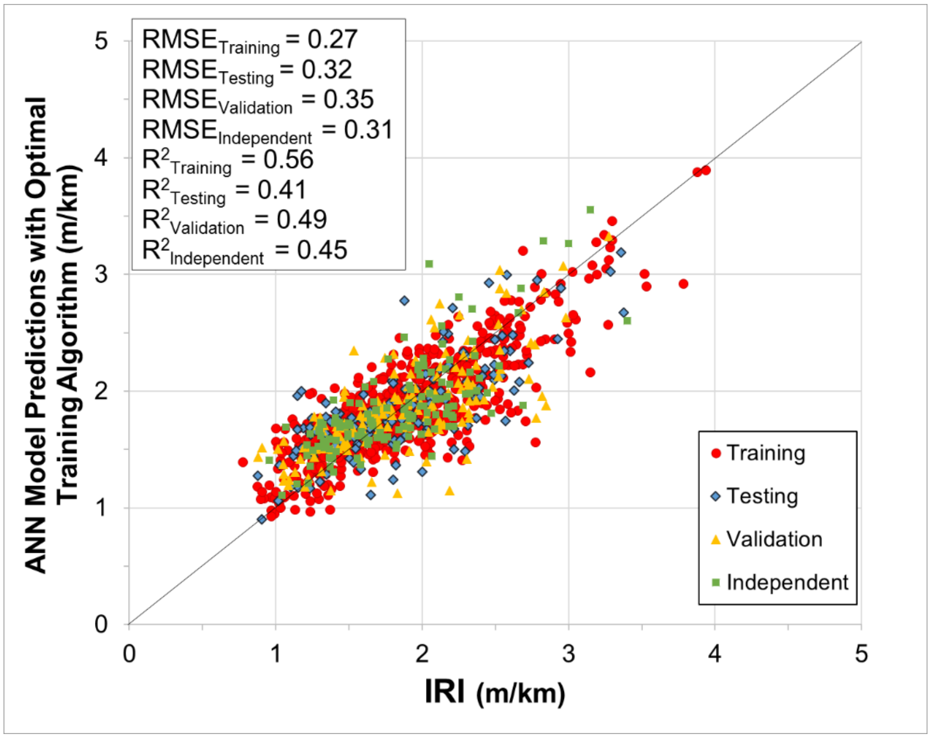


Figure 5-5 *Case 2 study field IRI values versus ANN model predictions with optimal training algorithm for training, testing, validation, and independent testing date sets*

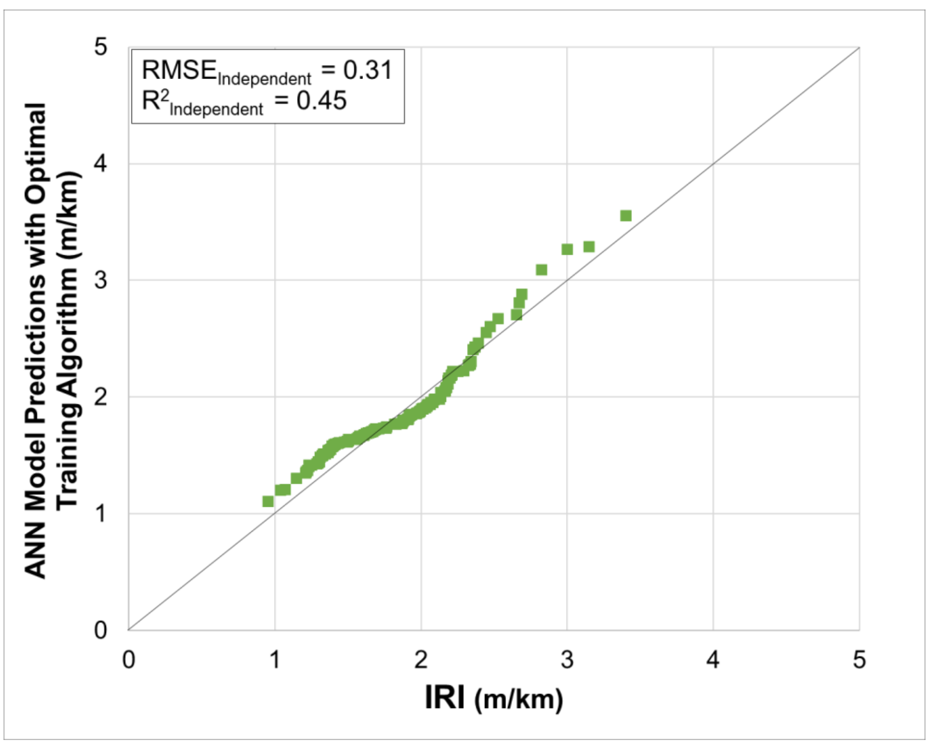


Figure 5-6 *Case 2 study field IRI values versus ANN model predictions with optimal training algorithm for independent testing data set*

5.4.3. Case 3 Study – 5 Input Variables

The Case 3 ANN network architecture is shown on Figure 5-7. Compared with case 1 and case 2, case 3 used many fewer input variables to predict concrete overlay IRI values. There were only five input variables to develop the prediction model, including construction design data, and traffic data. Furthermore, using a single hidden layer, varying from 10 to 100 neurons, 10 consecutive ANN models were developed in the MATLAB environment ANN model for each hidden-neuron case. Six different categories of training algorithms were used, and only one output layer is used in the ANN network architecture. There are only five input variables are used in case 3 compared with cases 1 and 2. Moreover, using only construction design and traffic data to develop ANN prediction model could save data collection time.

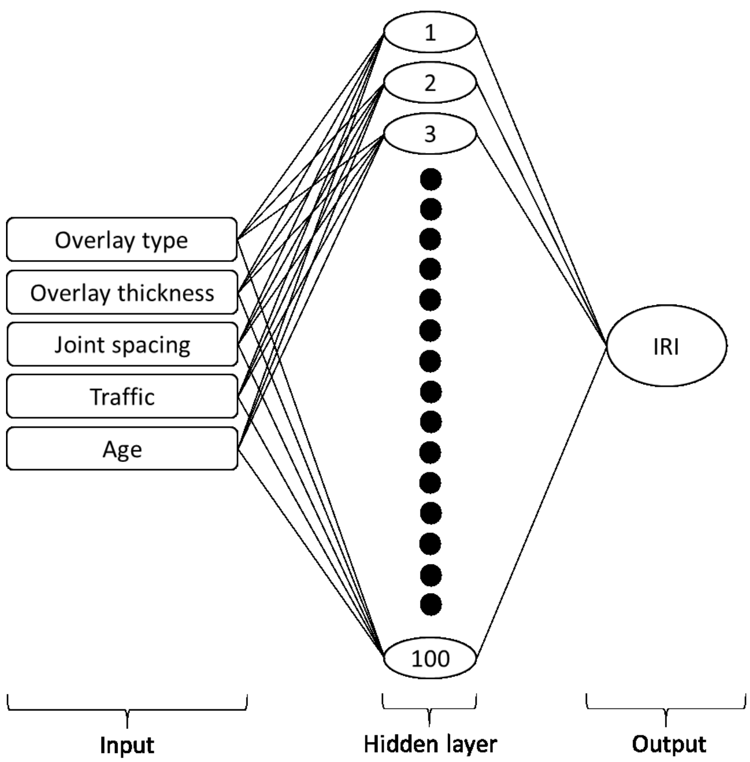


Figure 5-7 *ANN network architecture of case 3 study IRI values*

With respect to using fewer input variables, scaled conjugate gradient backpropagation was found to be the most optimal training algorithm, as shown in

Table 5-4. The LOE R^2 values for this case results were 0.60 for training dataset, 0.47 for testing, 0.49 for validation, and 0.48 for independent testing. In addition, The RMSE values for training were 0.29 m/km, 0.32 m/km for testing, 0.32 m/km for validation, and 0.31 m/km for independent testing.

The relationship between field measurement IRI values and predicted IRI values from the ANN model is shown in Figure 5-8. Compared with Figure 5-2, Figure 5-5, and Figure 5-8 statistical values, case 3 IRI prediction results have smaller independent testing RMSE values than case 1, but a number similar to case 2. Moreover, case 3 has higher LOE R^2 value according to independent testing results than either case 1 or case 2. Comparing the relationship between cases 2 and 3, construction design and traffic are more important variables than distress data in predicted Iowa concrete overlays performance. It seems that there was some error when performance data was collected. For example, while some of the project sections showed no distress or new construction on these overlay sections, the field measurements of IRI values in the IPMP database are not similar. Based on independent testing LOE R^2 and RMSE values, both case 2 and 3 ANN models are better than the case 1 ANN model. Again, the climate data is sparse, indicating that the relationship between Iowa concrete overlay performance and climate condition is most likely tenuous. Figure 5-9 presents only an independent testing Q-Q plot to compare two samples (field IRI and ANN model predictions with optimal training algorithm) of data to verify model assumptions. In this Q-Q plot (Figure 5-9), only one outlier is evident at the end of the range, and the RMSE value of independent testing is 0.31 m/km, indicating that the ANN model is a valuable and practical analysis tool.

Table 5-4 Case 3 ANN model training algorithms accuracy (R^2 and RMSE)

Training algorithms	Training		Testing		Validation		Independent testing	
	R^2	RMSE (m/km)	R^2	RMSE (m/km)	R^2	RMSE (m/km)	R^2	RMSE (m/km)
Levenberg-Marquardt	0.55	0.30	0.40	0.34	0.21	0.41	0.49	0.31
Bayesian regularization	0.57	0.28	0.52	0.36	0.10	0.40	0.46	0.31
BFGS	0.23	0.35	0.26	0.34	0.29	0.39	0.39	0.33
Resilient	0.59	0.28	0.26	0.38	0.16	0.43	0.47	0.33
Scaled conjugate gradient	**0.60**	**0.29**	**0.47**	**0.32**	**0.49**	**0.32**	**0.48**	**0.31**
Powell-Beale Restarts	0.42	0.33	0.37	0.34	0.22	0.39	0.48	0.30

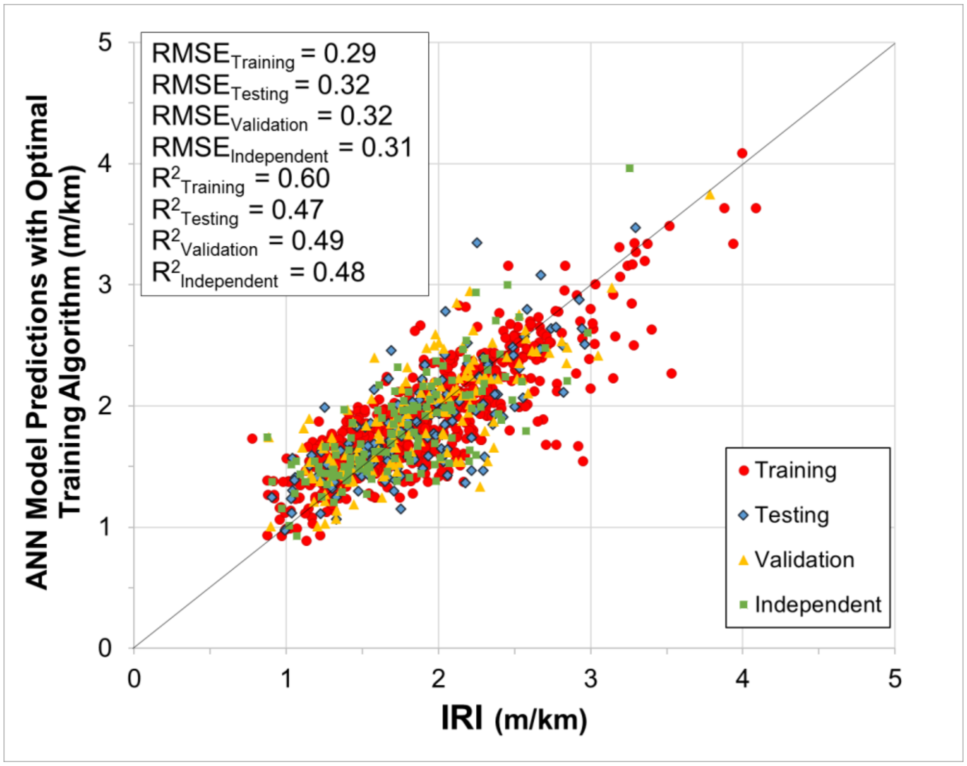


Figure 5-8 *Case 3 study field IRI values versus ANN model predictions with optimal training algorithm for training, testing, validation, and independent testing date sets*

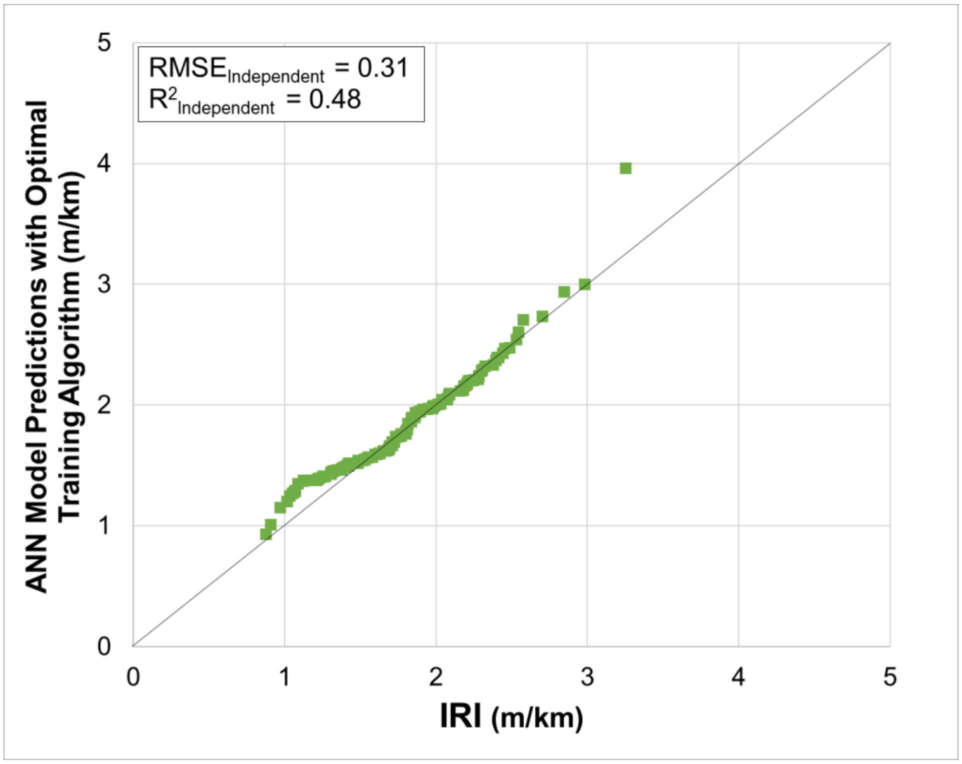
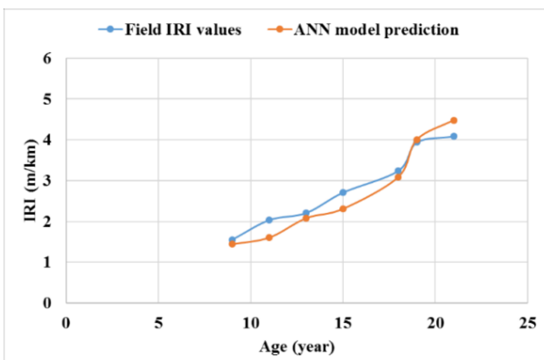


Figure 5-9 *Case 3 study field IRI values versus ANN model predictions with optimal training algorithm for independent testing data set*

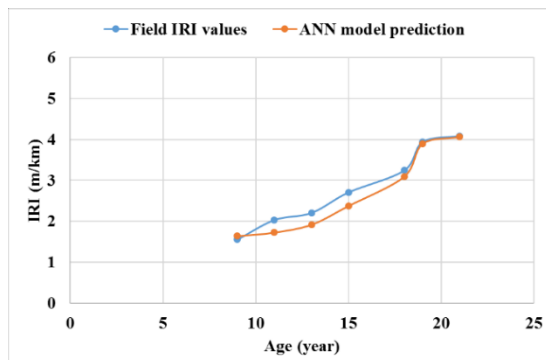
5.4.4. Comparative Analysis of the Results

The relationships between field-measured concrete overlays IRI values and ANN-predicted IRI values are shown in Figure 5-10 for different cases with different numbers of input variables. The example concrete overlay project was built in Pottawattamie County in 1993, with 7 inch concrete overlay thickness, and 20 foot joint spacing. As shown in Figure 5-10a, the plot reveals a tendency of the ANN model results to slightly underestimate IRI values compared to field measurements. Based on Figure 5-10b, field-measured IRI values from the Pottawattamie County concrete overlays project were close to the ANN model predicted IRI values.

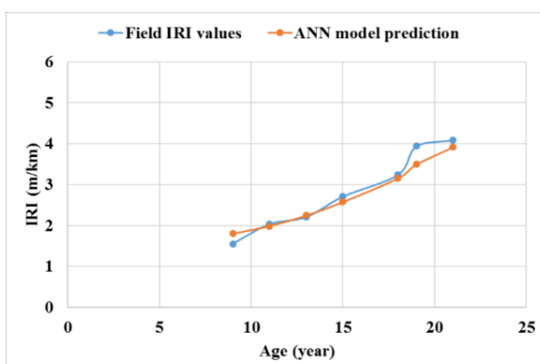
The concrete overlay performance prediction model developed through the case 2 study (RMSE: 0.23 m/km) was more successful than that from case 1 in predicting IRI (RMSE: 0.3 m/km). This shows that the annual average climate data currently available and used in this study might be not very effective in predicting such behavior of Iowa concrete overlays. Figure 5-10c is a plot of predicted versus field values for IRI when an ANN model was developed using case 3 input parameters. It can be observed that the ANN predictions were very close to the field measurements. As a result, examining these three ANN model predictions, case 2 and 3 studies not only used fewer input variables, but also produced an ANN model with the highest accuracy. Both case 2 and case 3 studies showed that the RMSE is only 0.23 m/km, less than 10% (0.25 m/km) of the range of IRI values (Note: the case 3 study RMSE is a little lower than that of the case 2 study). In a sense, the ANN model developed using case 2 and 3 studies could produce very accurate future IRI performance predictions for Iowa concrete overlays. In addition, if machine errors when ARAN collected performance data can be reduced, the case 2 study model becomes the most successful one in predicting IRI values.



(a)



(b)



(c)

Figure 5-10 *ANN predicted vs. field IRI values plot for (a) case 1. 14 input variables; (b) case 2. 9 input variables; (c) case 3. 5 input variables*

5.5 Conclusions and Recommendations

AI based alternatives such as ANNs have for decades been successfully used in the field of pavement design and analysis. The value of using ANN-based models to predict IRI is their potential for saving both time and budget for researchers and government agencies studying pavement rehabilitation and maintenance strategies. This study used Iowa concrete overlay historical performance data to develop ANN models to predict IRI values, with historical performance-related data that included pavement deterioration data, construction design data, traffic data and climate data. ANN model results were also used as statistical indices for developing recommendations on optimized IRI prediction models. Independent testing was used to determine the final model for predicting IRI values for Iowa concrete overlays. The major findings and recommendations of this study are summarized below:

- The prediction IRI results show that ANN models are valuable and practical analysis tools for predicting concrete overlay performance, and they specifically can help researchers and government agency in estimating IRI values for pavement management systems.
- Based on the case 1 study, the independent testing RMSE value of 0.34 m/km and small numbers of outliers (less than 10) in a Q-Q plot indicates that an ANN model is especially appropriate for investigating IRI values in evaluating long-term performance of Iowa concrete overlays.
- Based on the case 2 study, including climate data does not improve Iowa concrete overlay performance models very much because Iowa's annual average climate variation topography cause little variation with respect to climate.

- Based on the case 3 study, using only construction design and traffic data variables can produce high-accuracy prediction of Iowa concrete overlay performance.
  Comparison between field data and ANN prediction results showed that after a concrete overlays pavement has been constructed in Iowa, ANN models can accurately predict its future performance.
- With respect to PMIS data, while some project sections showed that there is no distress or new construction in these overlay sections, the field measurements of IRI values are not similar to one another. This explains why case 3 study predictions were better than those from the case 2 study.
- Since there are research studies discussing effects of climate conditions on concrete pavement performance, collecting data multiple times each year could possibly have a higher impact on the concrete overlay prediction model.

5.6 Acknowledgements

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CHAPTER 6. EVALUATION OF JOINT ACTIVATION AND JOINT SPACING IN CONCRETE OVERLAYS

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6.1 Abstract

Optimized joint spacing is crucial to ensure concrete overlay performance and service life, especially for the thinner concrete overlays. While pavement joints are used to control cracks in concrete slabs and help relieve stresses, not all sawn joints crack or “activate” initially. If cracks do not form below saw-cut joints, the effective slab length is high, potentially leading to excessive movements at the activated joints and increasing the risk of random cracking. The main purpose of this study was to investigate the differences in behavior between shorter (i.e. 1.83m. (6 ft.)) joint spacing and conventional (i.e. more than 3.66 m. (12 ft.)) joint spacing for concrete overlays.

Non-destructive testing (NDT) approaches such as ultrasonic low-frequency tomography are proving to be effective at detecting whether a saw-cut has been activated. A device known as “MIRA” has been shown to be efficient and cost-effective for this type of work, so in this study, a total of 54 concrete overlay project joints in Iowa were evaluated using an MIRA. The data indicated that approximately 60% to 70% of joints assessed were activated for the shorter joint spacing, while more than 95% of joints were activated for conventional joint spacing. These results were used to develop recommendations with respect to optimized joint spacing of Iowa concrete overlays.

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6.2 Introduction

Several parameters, including joint spacing, affect concrete overlay performance and service life. Contraction joints include those in the transverse and longitudinal directions. The primary purpose of installing joints is to control cracks in concrete slabs and to thereby help relieve stresses (Raoufi, Their, Weiss, Olek, & Nantung, 2009). Joint performance contributes to the long-term performance of concrete pavements and overlays (Khazanovich & Gotlif, 2003) in that it affects ride quality factors such as faulting, pumping, spalling, corner breaks, blow-ups, and D-cracking. The performance of joints is affected by joint spacing as well as saw-cut depth and timing (American Concrete Pavement Association, 1992).

While saw-cut joints are intended to control crack location, not all joints crack or "activate" initially, either because of environmental conditions (limited temperature variation), or because joint spacing is too short for the slab thickness. If cracks do not form below the saw-cut joints, then the effective length of the slabs is too high, potentially leading to large movement at the activated joints and increasing the risk of random cracking.

In the past, coring or digging out shoulders were the only approaches available to determine whether a saw-cut had been activated, but such methods are costly and time-consuming, making it difficult to evaluate multiple joints or projects. A more recent alternative is to use non-destructive testing (NDT) techniques.

MIRA is a device that uses ultrasonic shear-wave tomography and imaging to identify voids in reinforced or plain concrete. The device uses an ultrasonic pitch-catch method and an antenna composed of an array of dry point contact (DPC) transducers to create a three-dimensional (3-D) image (Popovics, et al., 2017). This technology has been used successfully for determining slab thickness, location of steel bars, and detection of de-laminations.

Based on recent research at the University of Illinois, the MIRA can also be used detect joint activation (Tran, Roesler, & Popovics, 2018) using data selected from some of its transducers. One source of variation is when tests are conducted over tightly-closed cracks, because the acoustic signal may not be reflected off the crack face (Tran, et al., 2018).

This study included an investigation of overlay projects of various ages and a review of their construction and performance. The test sections included various joint spacing, thickness, and mixtures both with and without structural fibers.

The purpose of the work described in this paper was to investigate differences in behaviour between shorter (i.e. 1.83 m. (6 ft.)) joint spacing and conventional (i.e. more than 3.66 m. (12 ft.)) joint spacing for concrete overlays.

6.3 Methodologies

6.3.1. Iowa Concrete Overlays Field Joint Activation Data Collection

In this study, 54 concrete overlay projects, including 52 historical concrete overlay projects and 2 test sections, were assessed using the ultrasonic shear-wave tomography (MIRA) device.

Table 6-1 and Table 6-2 describe the projects and test sections evaluated.

As shown in

Table 6-1, there were 52 concrete overlay projects, with a total of 652 joints evaluated. The database includes two types of overlays: unbonded concrete-on-concrete (UBCOC), and bonded concrete-on-asphalt (BCOA). Overlay thickness ranged from 101.6 mm. (4 in.) to 177.8 mm. (7 in.), and transverse joint spacing ranged from 1.68 m. (5.5 ft.) to 12.19 m. (40 ft.). In 23 of the projects the MIRA testing results were verified by digging along the side of the pavement. Based on this comparison, the MIRA testing exhibited 86% accuracy for predicting crack deployment.

As shown in Table 6-2, there were two concrete overlay test sections, one in Mitchell County, the other in Buchanan County. At the Mitchell county BCOA test section, constructed in summer 2017, the concrete overlay thicknesses were 101.6 mm. (4 in.) and 152.4 mm. (6 in.). Transverse joint spacing ranged from 1.83 m. (6 ft.) to 6.10 m. (20 ft.), and there were mixtures both with and without synthetic fibers. At the Buchanan county UBCOC test section, constructed in summer 2018, the concrete overlay thickness was 152.4 mm. (6 in.), the transverse joint spacing ranged from 1.68 m. (5.5 ft.) to 12.19 m. (40 ft.), and again there were mixtures both with and without synthetic fibers.

Work at both of these two test sections included considering the visual joint activation data collected before the shoulders were paved and the MIRA testing results collected at 3 month intervals. Visual joint activation data were collected on the central (30.48 m. (100 ft.)) portion of each section at different joint spacing. The test was repeated 10 times at each joint, and the results were represented as normalized energy.

Table 6-1 Joints assessed using the MIRA on existing sections

		Number of joint samples
Types of concrete overlay	BCOA	420
	UBCOC	232
Thickness (mm.)	101.6	87
	127.0	95
	152.4	431
	177.8	39
Joint spacing (m.)	1.68 to 2.29	148
	3.35 to 3.81	236
	4.27 to 4.57	159
	6.10 to 12.19	109

Table 6-2 Joints assessed using the MIRA on test sections

Location and types of overlays	Thickness (mm.)	Joint spacing (m.)	Number of joints assessed using visual observation	Number of joints assessed using MIRA
Mitchell county (BCOA)	101.6	1.83	16	15
		3.66	8	12
		4.57	7	12
		6.10	5	12
	152.4	1.83	16	15
		3.66	8	12
		4.57	7	12
		6.10	5	12
Buchanan county (UBCOC)	152.4	1.68	18	15
		3.66	8	12
		4.57	7	12
		6.10	5	12
		9.14	3	7
		12.19	3	7

6.3.2. Analytical Investigations Using MIRA Model

Joint activation data were collected using a MIRA device whose antenna is composed of a 4 by 12 array of point transducers. The system uses an ultrasonic pitch-catch method to evaluate internal defects in a concrete element. In the pitch-catch method, one transducer sends out a stress-wave pulse at 35 kHz, and a second transducer receives the reflected pulse. The MIRA can detect whether a crack is deployed in a sawn joint in concrete based on the fact that an air gap in a crack will reflect the pulse, while an un-cracked section will permit the pulse to pass through relatively unchanged. The machine is placed over the saw-cut so that half the transducers are on each side of the cut. Interpretation of the data collected by the device to assess joint activation has been developed at University of Illinois in order (Tran, et al., 2018).

The normalized energy was transmitted from antenna No. 2 and calculated based on the energy (E_i) received at sensors 7 through 12, divided by the energy received at sensor 6 (E_6) (Tran, et al., 2018).

$$\text{Normalized energy}_i = \frac{E_i}{E_6} \; (i = 7, \dots, 12). \qquad \text{(Equation 6-1)}$$

As shown in Figure 6-1, if the normalized energy at receiver 7 is higher than 0.35, this indicates that there was no crack deployment at the joint because energy was transferred to the sensor on the other side of the saw-cut. Conversely, receiver 7 normalized energy lower than 0.3 suggests that there was crack deployment at the joint. A normalized energy reading lying between 0.35 and 0.3 indicates either a very tight crack beneath the saw-cut or no crack beneath the saw-cut (Tran et al., 2018) and the data in such cases are reported as inconclusive. Tran reported that, based on their laboratory work, the method was correct about 80% of the time.

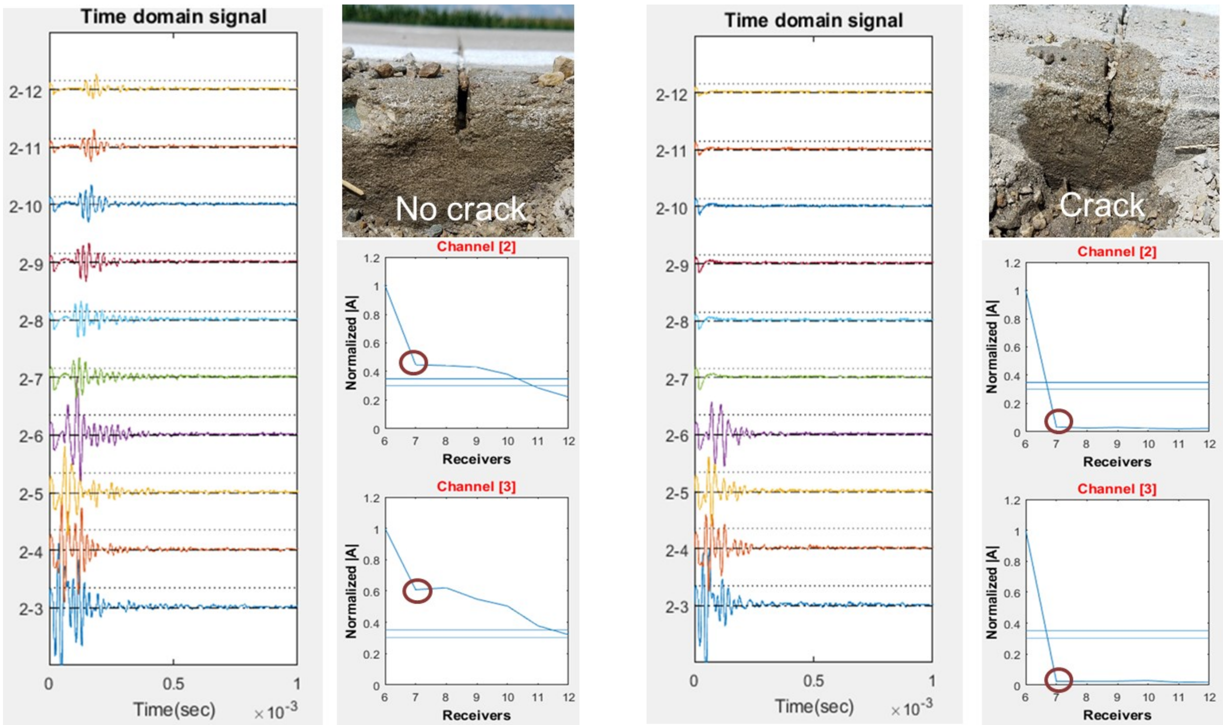


Figure 6-1 *MIRA analysis results for joint activation*

6.4 Results and Discussion

6.4.1. Different Types of Concrete Overlays (in-service concrete overlays sites)

Four different types of concrete overlays have been constructed in Iowa: bonded concrete-on-concrete (BCOC), unbonded concrete-on-concrete (UBCOC), bonded concrete-on-asphalt (BCOA), and unbonded concrete-on-asphalt (UBCOA) (Gross et al., 2017). This work was focused on investigating joint spacing in UBCOC and BCOA because BCOC joints are placed to match those in the underlying pavement while UBCOA slabs are greater than 152.4 mm. (6 in.) in thickness, and therefore are not built with short joint spacing.

Figure 6-2 displays the percentage of joints that have activated for the different types of overlay. As shown in the figure, 88% of BCOA joints have activated, while 91% of UBCOC joints have activated. In both cases, about 2% of the joints tested were considered inconclusive.

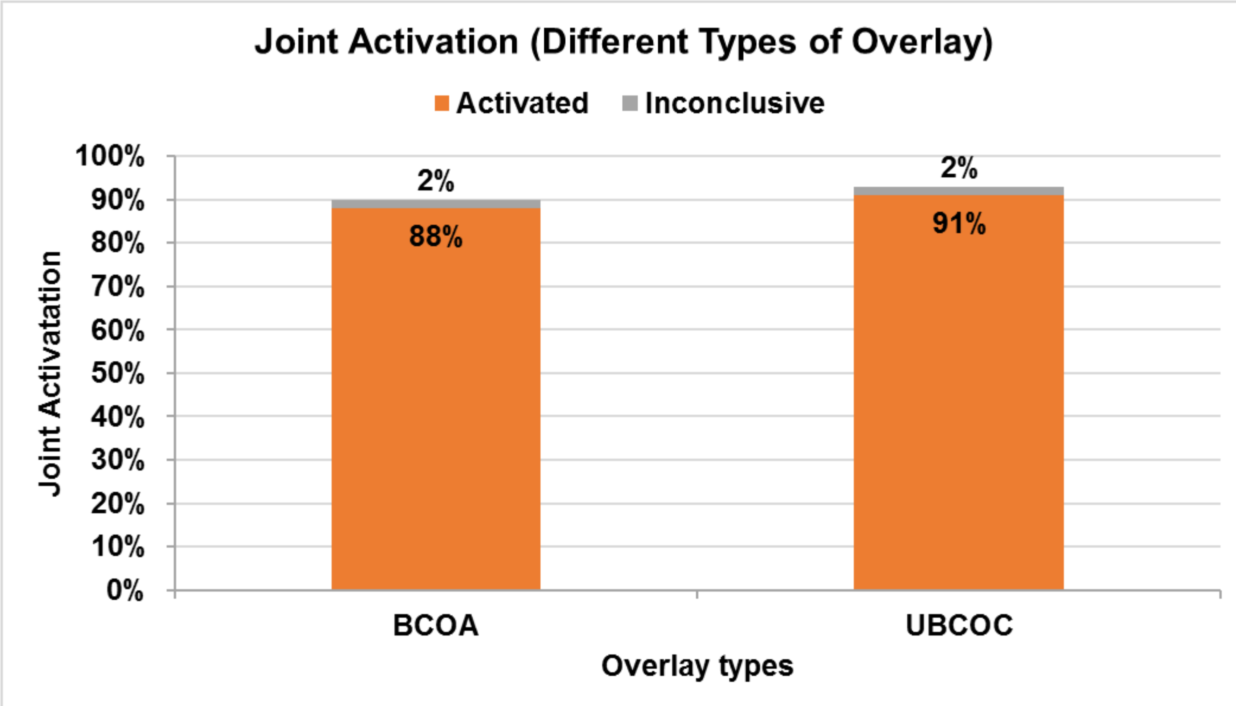


Figure 6-2 *Comparison of joint activated for different types of concrete overlays*

6.4.2. Different Joint Spacing of Concrete Overlays (in-service concrete overlays sites)

Figure 6-3 shows joint activation percentages for different joint spacing. As shown in the figure, activation rates increased with increasing joint spacing, with nearly all slabs longer than 4.3 m having activated joints. Longer joint spacing is therefore associated with an increase in the percentage of activated joints.

This is most likely due to increase in shrinkage-related stresses as joint spacing increases (Roesler & Wang, 2011). The Darter and Barenberg (1977) equation shows that longer joint spacing will lead to larger joint opening or increase the risk of random cracking (Zhang & Li, 2001).

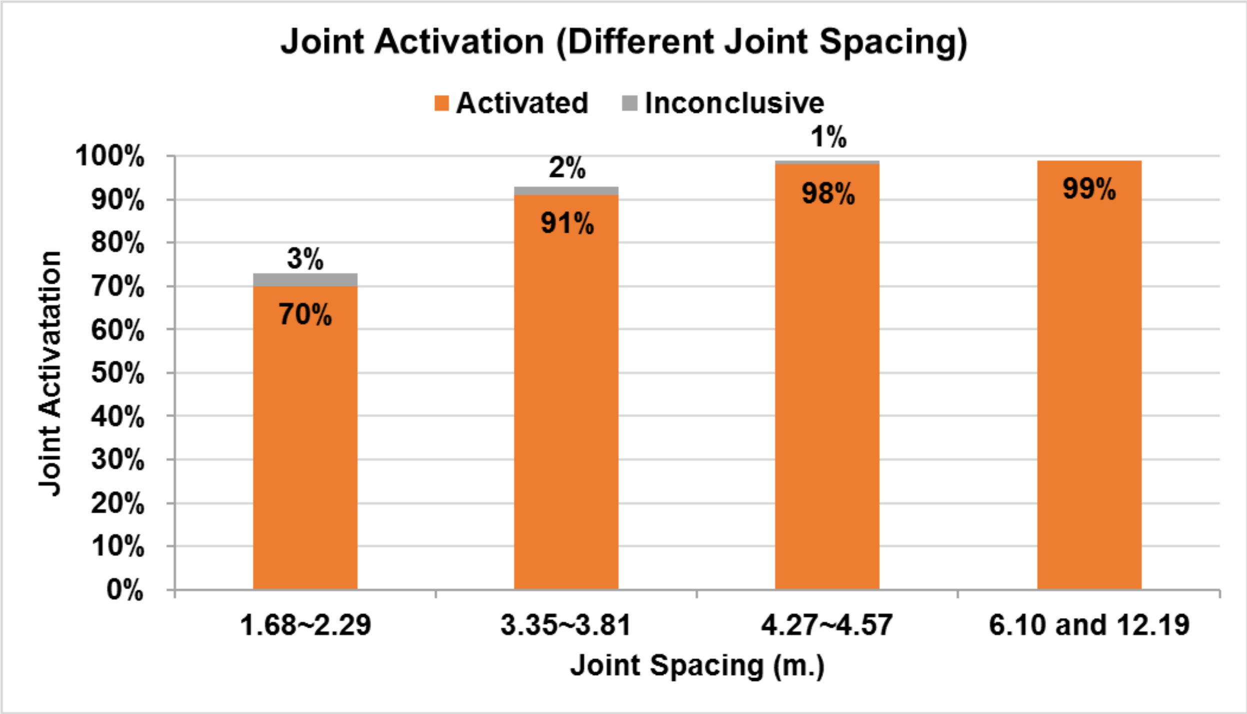


Figure 6-3 *Comparison of joint activated for different joint spacing*

6.4.3. Different Thickness of Concrete Overlays (in-service concrete overlays sites)

Figure 6-4 shows joint activation percentages for different thickness of concrete overlays. As shown, activation rates increased with increasing thickness up to the 177.8 mm. (7 in.) sections that were all activated.

Two factors are likely to contribute to increased activation rates with increasing thickness:

- Most of the thicker panels were constructed using larger joint spacing (Davids & Mahoney, 1999).
- Curling stresses increase with increasing pavement thickness. As slab thickness increases, the temperature differential between the top and bottom of the slab also increases, leading to increased stress (Shoukry, William, & Riad, 2007).

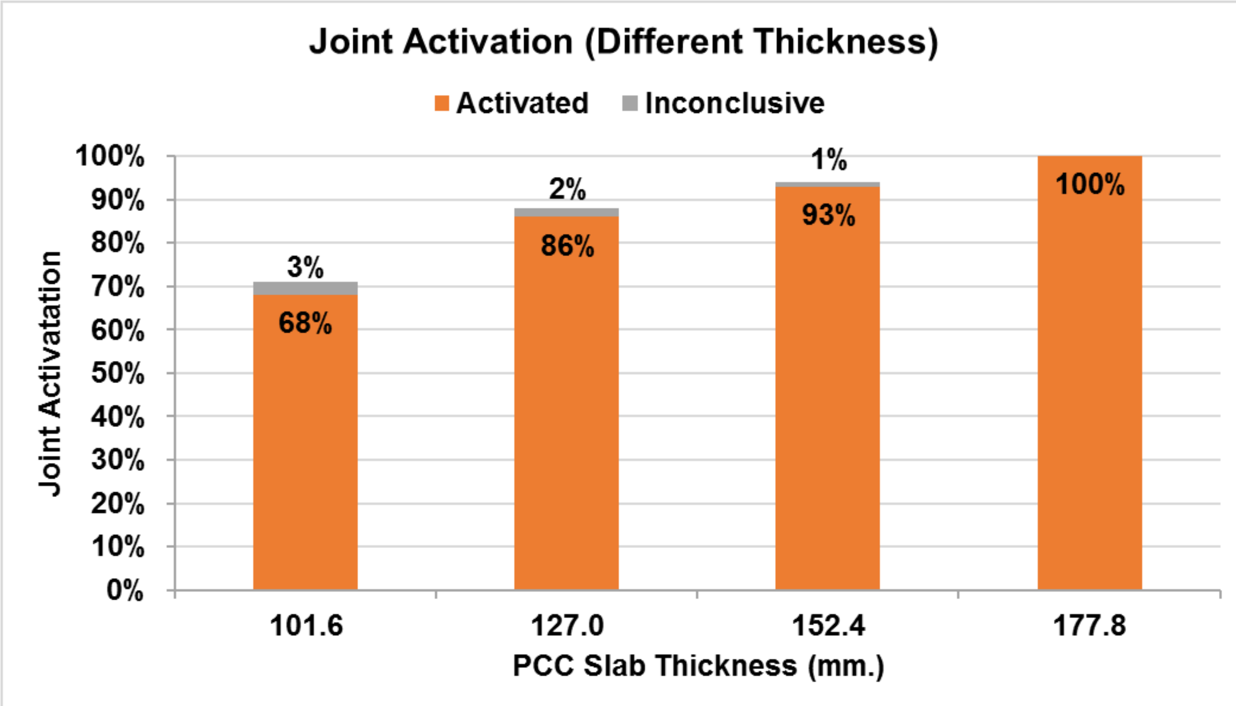


Figure 6-4 *Comparison of joints activated for different thickness*

6.4.4. Test section in Mitchell County, Highway 105

The Mitchell County overlay test section was constructed in August 2017. The overlay is a BCOA, with two thicknesses of 101.6 mm. (4 in.) and 152.4 mm. (6 in.), and joint spacing ranging from 1.83 m. (6 ft.) to 6.10 m. (20 ft.) (Table 6-2). The test section included concrete mixtures both with and without fiber dosed at 2.37 kg/m^3 (4 lb/yd^3).

Figure 6-5 presents joint activation percentages for the various sections within this test section. Initial joint activation data were collected by visual means before traffic was allowed on the pavement, and reassessed periodically using the MIRA.

For a 1.83 m. (6 ft.) joint spacing, only 16% of joints were activated after one day, and this increased over time to more than half after 180 days. Activation appeared to decrease at 270 days, but this is most likely a biased result because slabs were hot and expanded and joints were closed at the time testing was conducted (Tran, et al., 2018). For the 3.66 m. (12 ft.) spaced joints

(Figure 6-5b), 31% of joints were activated after one day, and this increased over time until all joints were activated at 270 days. Figure 6-5c and Figure 6-5d show increasing activation at earlier ages with increasing panel length.

Figure 6-5 also shows that addition of fibers did not appear to affect the rate of joint activation. This is not surprising because the fibers used would not be expected to influence the stress required to crack the concrete, but could help to control crack widths (Bischoff, 2003, Altoubat & Lange, 2001).

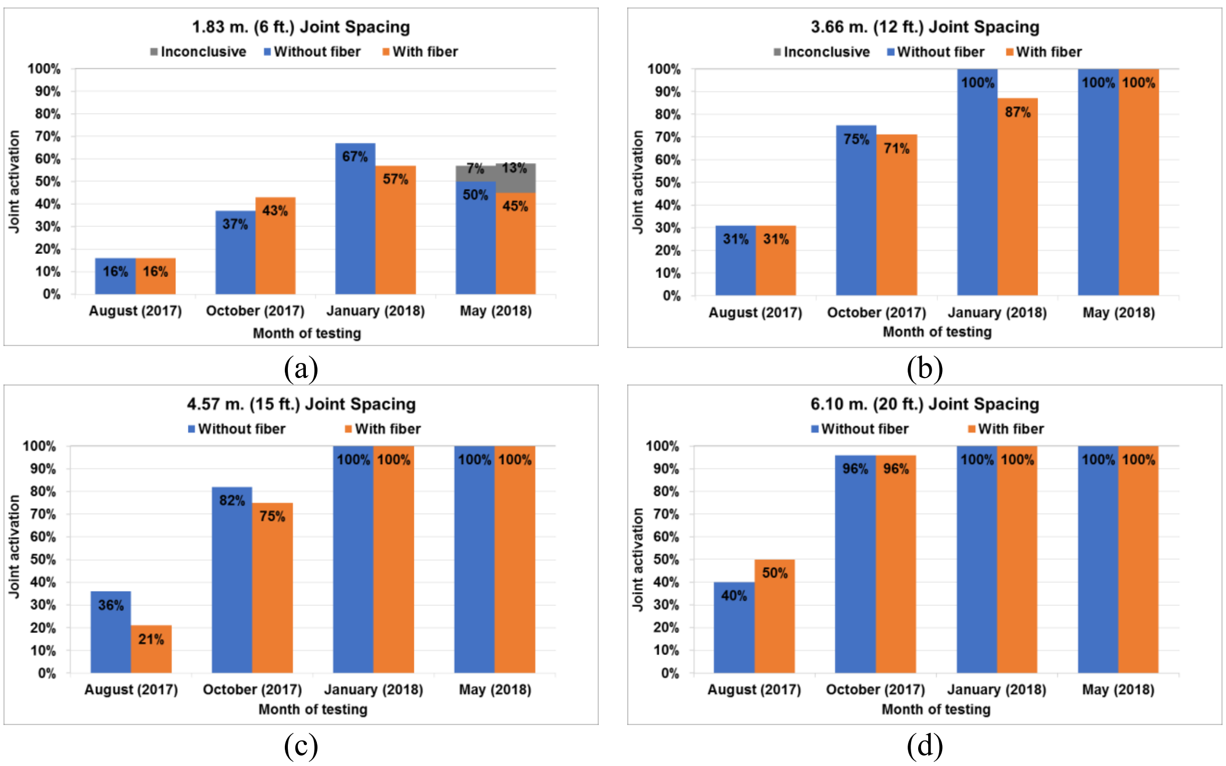


Figure 6-5 *Joints activated for different joint spacing of Mitchell County test section*

As shown in Figure 6-5, longer joint spacing lead to an increasing percentage of activated joints, similar to the historical test data.

An equation by Bradbury (1938) provides insight into the parameters influencing pavement stresses. The curling stress of concrete can be estimated as:

Curling interior stress, $\sigma_t = \frac{E\alpha\Delta T}{2}[\frac{C_x+\mu C_y}{1-\mu^2}]$ (Equation 6-2)

Curling edge stress, $\sigma_t = \frac{CE\alpha\Delta T}{2}$ (Equation 6-3)

where σ_t is slab edge curling stress; $C = C_x$ and C_y are the stress coefficients for a finite slab; E is the modulus of elasticity of pavement; α is the coefficient of the thermal expansion; ΔT is the temperature differential between the top and bottom of the slab.

As seen in Figure 6-6, based on the equation, a higher ratio of slab length to radius of relative stiffness (L/ℓ) in the range from 1 to 8 leads to an increase in stress coefficient (C) for a finite slab.

The radius of relative stiffness (ℓ) is (Westergaard, 1927)

$$\ell = \sqrt[4]{\frac{Eh^3}{12K(1-\mu^2)}}$$ (Equation 6-4)

where E is the pavement modulus of elasticity; h is the pavement thickness; μ is the Poisson's ratio of the PCC; K is the modulus of subgrade reaction.

Since outside this range the slab proportions do not affect the stress coefficient, the temperature differential between the top and bottom of the slab becomes the most important parameter w.r.t. curling stress.

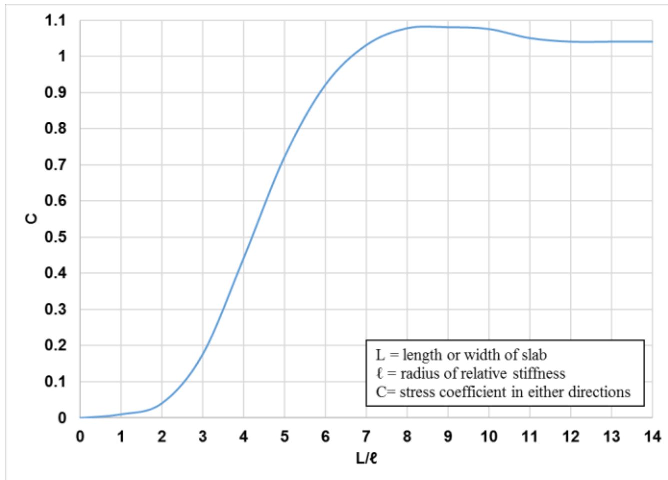
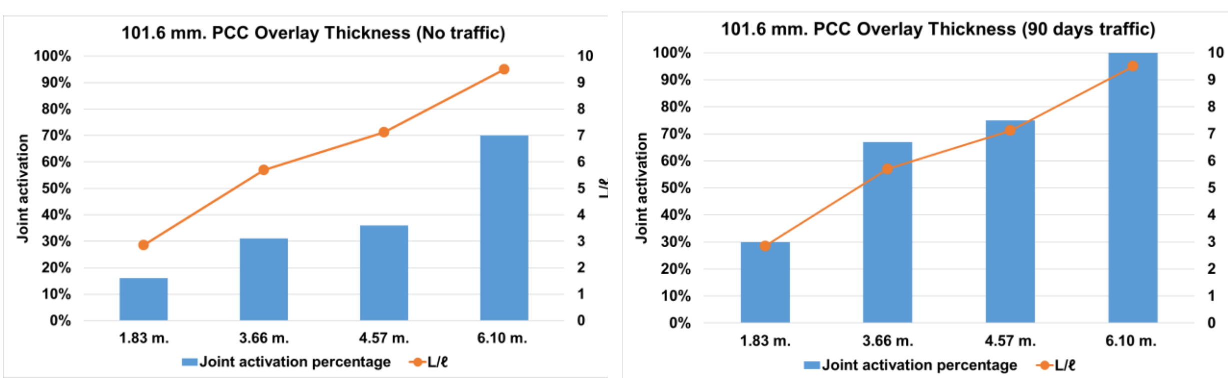
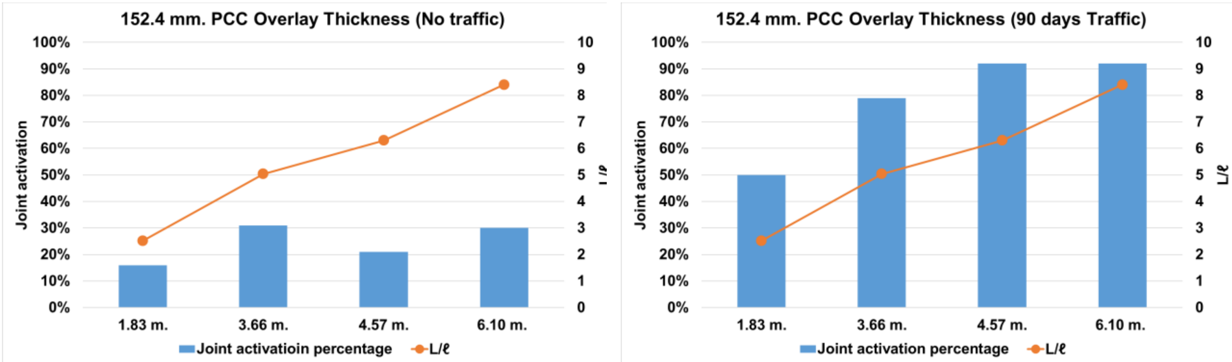


Figure 6-6 *Differential curling stress coefficient for different values of slab length and the radius of relative stiffness ratio (L/ℓ) (redrawn from Bradbury, 2002)*

Figure 6-7 shows the correlation between joint activation and the L/ℓ ratio. For the 101.6 mm. (4 in.) thick test sections, the L/ℓ ratio ranges between 2.85 and 9.50, while for the 152.4 mm. (6 in.) sections, the L/ℓ ratio ranges from 2.52 to 8.40. The similarities between the trends indicate that the L/ℓ ratio is a driving factor behind the stresses responsible for joint activation.



(a) (b)



(c) (d)

Figure 6-7 *Joint activated vs relative stiffness and joint spacing ratio for Mitchell County concrete overlays test section*

6.4.5. Test section in Buchanan County V62

The Buchanan County test section was constructed in August 2018. The overlay is an UBCOC with a thickness of 152.4 mm. (6 in.) and joint spacing ranging from 1.68 m. (5.5 ft.) to 12.19 m. (40 ft.) (Table 6-2). Geofabric was used for the interlayer. The mixtures included both plain and fiber-reinforced concrete.

Figure 6-8 presents the data for different joint spacing just after the joint was cut and before traffic was applied. Every joint was activated when the transverse joint spacing was larger than 6.10 m. (20 ft.), and the L/ℓ ratio was higher than 8.

Therefore, due to the traffic loading, equal or larger than 6.10 m. (20ft.) joint spacing concrete overlays have higher probability provided cracks on the middle of slab than other slab size. As the results, excluding the age effects, it can be recommended that L/ℓ value should be lower than 8 for UBCOC.

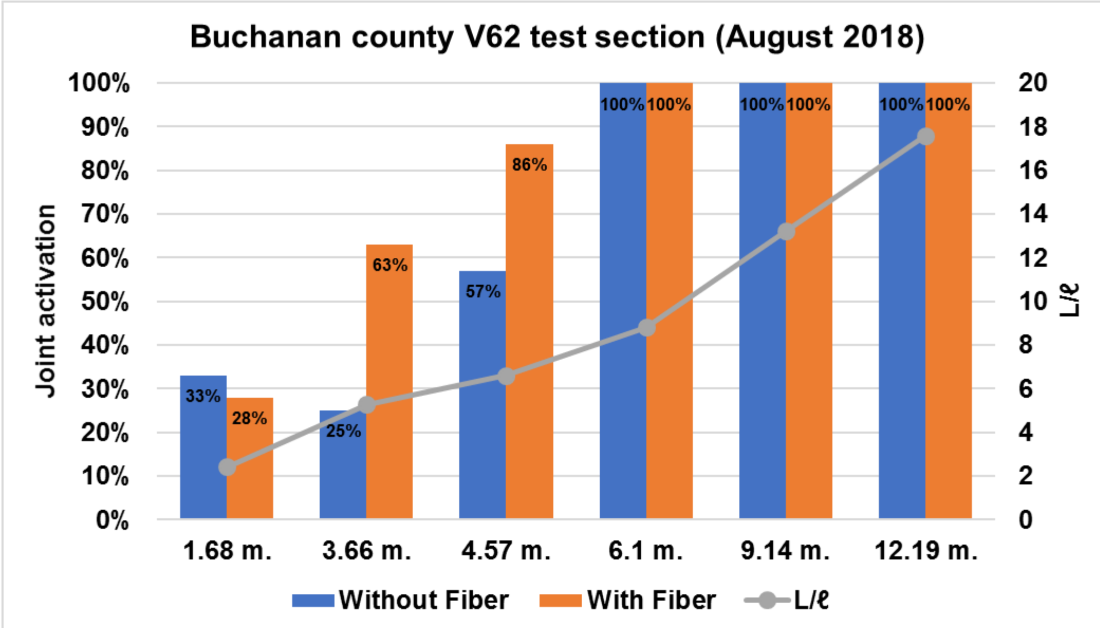


Figure 6-8 *Joint activated vs relative stiffness and joint spacing ratio for Buchanan county concrete overlays test section*

6.5 Conclusions and Recommendations

This study used MIRA to evaluate rates of joint activation in concrete overlays and to develop recommendations on joint spacing for Iowa concrete overlays. The major findings and recommendations are summarized as follows:

- Based on MIRA testing results, joint activation rates were similar for both BCOA and UBCOC overlays.
- Greater overlay thickness and longer joint spacing lead to increased joint activation rates, consistent with published models.
- Joint spacing should be based on L/ℓ value between 4 and 7.

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CHAPTER 7. CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

7.1 Summary

This research study evaluated the performance of concrete overlays built in Iowa over the last 30 years. An Iowa concrete overlay distress data set obtained from Iowa Pavement Management Program (IPMP) was cleaned by eliminating irrelevant, inaccurate, and incomplete records. The cleaned data were examined to identify Iowa concrete overlay distributions based on different overlay types, different slab thickness types, different transverse joint spacing types, and various performance measures, including the pavement condition index (PCI) and the international roughness index (IRI). Historical IRI and PCI records of Iowa concrete overlays in cleaned data were also analyzed by identifying changes in PCI and IRI values during service life. Even though Iowa concrete overlay historical performance data shows that Iowa concrete overlay can be extended over original pavement by at least 20 years of service life, the historical performance-related data showed that Iowa concrete overlay performance still can be improved, and the service life can be extended by more than 20 years. According to the database, some of the data sets exhibit clear division that may be reviewed, and if construction quality is improved, premature failure will be eliminated and concrete overlays service life may be further increased.

Construction Design parameters are one of the important factors affecting concrete overlay long-term performance. In Iowa, most design procedures still follow empirical methods such as those in the 1993 AASHTO Guide for Design of Pavement Structures. Since such empirical methods may not include existing pavement performance that is significant for calculating concrete overlay long-term performance, when compared to the Mechanistic-Empirical design software such as AASHTOWare Pavement ME Design (Version 2.3.1), empirical methods sometimes provide inadequate design guidance for Iowa concrete overlays.

AASHTOWare Pavement ME Design (Version 2.3.1) was used to identify effects of joint spacing, thickness, and existing pavement performance on concrete overlay service life. Results were compared with historical performance-related data and Pavement ME Design software results to develop recommendations on optimized joint spacing.

An artificial neural networks (ANN) modeling approach was used to provide high-accuracy prediction of concrete overlay long-term performance. ANNs have been successfully used in pavement analysis, design, and prediction for many years. An ANN model was developed in the MATLAB environment, and comparison between concrete overlay field-measured performance and ANN-predicted performance values indicate that ANN models can accurately predict future performance of Iowa concrete overlay pavement based only on using construction design and traffic data variables.

Panel size is a major influencing factor for concrete overlay performance and service life. Although there are many different panel sizes used in concrete overlay pavement construction in Iowa, no research study has identified an optimum joint spacing. While pavement joints are used to control cracks in concrete slabs and to help relieve stresses, not all sawn joints crack or "activate" initially. MIRA (Ultrasonic Shear-wave Tomography) is a non-destructive testing (NDT) testing method that can be used to identify joint activation in concrete pavement. Compared to shoulder excavation of transverse joints, the MIRA testing showed 86% accuracy in predicting joint activation. The results indicated that more than 95% of joints were activated for longer/conventional joint spacing, while only about 60% to 70% of joints were activated for shorter joint spacing in concrete overlay pavement.

This dissertation developed a comprehensive Iowa concrete overlay database. According to this database, using multiple analysis methods, including historical performance data, Pavement ME design software, ANN prediction model, and MIRA testing, can help identify the effects of overlay types and design features (including overlay thickness and joint spacing) on concrete overlay long-term performance.

7.2 State of the Art Contributions to Engineering Research and Practice

The major state-of-the-art contributions to engineering research and practice from this research are summarized below:

- Providing the first comprehensive concrete overlay long-term performance evaluation study.
- Developing a high-accuracy pavement performance prediction model for Iowa concrete overlays.
- Optimizing concrete overlays panel size for government agencies.

7.3 Noted in the Papers

The major conclusions from this study are summarized follows:

- According to PCI ratings, 89% of concrete overlay projects have PCI values greater than 60% and about 93% of concrete overlay projects have IRI values lower than 2.7 m/km (170 in/mile). These findings indicate that concrete overlays are effective in expanding the service life of existing pavements. For example, PCI values of UBCOCs were greater than 60% for service lives up to 20 years, and IRI values of UBCOCs were lower than 2.7 m/km (170 in/mile) for service lives up to 25 years. The PCI values of UBCOA and BCOA were higher than 60% for service lives up to 35 years, and the IRI values of UBCOA and BCOA were lower than 2.7 m/km (170 in/mile) for service lives up to 35 years.

- Performance and service life varied for different types of concrete overlays. During the first 10 years of service, all four types of concrete overlays exhibited similar performance. Between 11 and 20 years of service, UBCOC, BCOA, and UBCOA performed better than BCOC. Between 21 and 30 years of service, BCOA and UBCOA performed better than UBCOC. For more than 30 years of service, UBCOA performed better than BCOA.
- Pavement thickness can affect concrete overlay performance and service life. In general, greater overlay thickness leads to increased service life. UBCOA can provide better performance in terms of PCI and IRI trends than other concrete overlay types. UBCOC is a concrete overlay type with a broader thickness range (from 127-mm. (5 in.) to 203-mm. (8 in.)) than the other concrete overlay types. Performance of UBCOC is similar to UBCOA in thickness ranges of 152-mm. (6 in.) to 203-mm. (8 in.).
- Joint spacing can also affect concrete overlay performance and service life. While shorter joint spacing (i.e., 1.7-1.8 m. (5.5-6 ft.)) for UBCOC may present more advantages than larger joint spacing (i.e., longer than 3.8 m. (12 ft.)), BCOA and UBCOA projects with joint spacing larger than 4.6 m. (15 ft.) still show performance comparable to joint spacing shorter than 4.6 m. (15 ft.).
- Increasing existing pavement thickness leads to extension of overlay service life, depending on the design of the overlay.
- When a PCC overlay is less than 178-mm. (7-in.) thick, 3.7-m. (12-ft.) joint spacing overlays have similar service lives to those for a 6.1-m. (20-ft.) joint spacing. When the overlay thickness is greater than 178-mm. (7-in.), a shorter joint spacing appears to be preferred.

- Comparison of historical performance-related data with Pavement ME Design software results indicates that the Pavement ME Design software is conservative with respect to predicting concrete overlay service life.
- Since the predicted IRI results show an ANN model to be a valuable and practical analysis tool for predicting concrete overlay performance, ANN models can help researchers and government agencies to estimate IRI values for pavement management systems.
- The ANN model independent testing RMSE value of 0.34 m/km and small numbers of outliers (less than 10) in a Q-Q plot indicate that an ANN model is especially appropriate for investigating IRI values in evaluation of Iowa concrete overlay long-term performance.
- Climate data does not improve Iowa concrete overlay performance models much because Iowa's annual average climate data Iowa topography result in climate data not having much variation.
- Using construction design and traffic data variables leads to high-accuracy Iowa concrete overlay performance prediction.
- Comparison between field data and ANN prediction results showed that, after construction of a concrete overlay pavement, ANN models can accurately predict Iowa concrete overlay pavement future performance.
- The MIRA accuracy is around 86%, the accuracy of this device could be increased due to the University of Illinois Urbana-Champaign (UIUC) software improvements.
- Based on MIRA testing results, joint activation rates were similar for both BCOA and UBCOC overlays.

- Greater overlay thickness and longer joint spacing lead to increased joint activation rates, consistent with published models.
- Joint spacing should be based on L/ℓ value between 4 and 7.

7.4 Recommendations

The major recommendations from the dissertation are summarized below:

- To date, more than 2,000 miles of concrete overlay pavements regularly have been constructed on Iowa roadways. However, around 1,500 miles of concrete overlay roads were included as of 2014 in this dissertation, since approximately 600 miles of concrete overlay roads have been built after 2014, the data collection process is recommended to be continued.
- No local calibration study on Iowa concrete overlays system (bonded or unbonded concrete overlays) has been conducted for Pavement ME Design. Although, the Pavement ME Design software predicting concrete overlay service life is similar to historical data service life, the Pavement ME Design predicting line is conservative in predicting concrete overlay service life. Therefore, development of Iowa concrete overlay calibrated performance prediction models is recommended.
- There are many studies that discuss climate condition effects on concrete pavement performance, so if data are collected multiple times each year, climate data might possibly have more significant impact on the concrete overlay prediction model.
- Most short joint spacing used in Iowa concrete overlays are constructed as 1.83 m. × 1.83 m. (6 ft. × 6 ft.), and not as 2.44 m. × 2.44 m. (8 ft. × 8 ft.). The 2.44 m. × 2.44 m. (8 ft. × 8 ft.) size of panel is recommended to construct and investigate, because this might increase the joint activation percentage, while the L/ℓ ratio would remain at a low value.

- Due to the effects of traffic loading, equal or larger than 6.10 m. (20ft.) joint spacing concrete overlays have a higher probability of providing cracks at the slab center than other slab sizes. As a result, excluding age effects, it can be recommended that 6.10 m. (20 ft.) or larger joint spacing would be too large for UBCOC, so such a joint spacing is not a recommended design size for UBCOC.

APPENDIX CONCRETE OVERLAY PHASE 2-A FINAL REPORT ANALYSIS SECTION

The appendix shows the detail of AASHTOWare Pavement ME Design, BCOA-ME, and MIRA testing results.

AASHTOWare Pavement ME Design

Table 1 presents the structural design parameters of two concrete overlays types (JPCP over JPCP, and JPCP over AC) used in analytical investigations by Pavement ME Design. A 30-year designed service life with a 50% reliability was utilized.

Table 1 Structural design parameters of Pavement ME design on Iowa concrete overlays projects

Design parameters (type)	JPCP over AC (BCOA)	JPCP over JPCP (unbonded) (UBCOC)
Traffic (ADT)	750	
Traffic (AADTT)	75	
Climate station	Des Moines	
Joint spacing (ft.)	12 × 12 12 × 15 12 × 20	12 × 12 12 × 15 12 × 20
Thickness (in.)	4 to 6	5 to 6
Existing AC/PCC layer thickness (in.)	4 and 6	6
Interlayer thickness (in.)	N/A	1

Figure 1 and Figure 2 shows Pavement ME Design IRI predictions for BCOA and UBCOC designs with 12-foot joint spacing for each combination of overlay thickness and existing pavement thickness.

The key findings observed in Figure 1 on cases of the 12-foot joint spacing of 4 to 6 inches thickness BCOA are listed as follows:

- The IRI prediction curve for 4-inch overlays thickness increased to more than 170 in/mile after 16 years at selecting 4-inch existing AC layer thickness and after 22 years at selecting 6-inch existing AC layer thickness.
- The IRI prediction curve for 5-inch overlays thickness increased to more than 170 in/mile after 28 years at selecting 4-inch existing AC layer thickness and below 170 in/mile over the first 30 years at selecting 6-inch existing AC layer thickness.
- The IRI prediction curve for 6-inch overlays thickness were maintained at or below 170 in/mile over the first 30 years at selecting 4-inch existing AC layer thickness and at selecting 6-inch existing AC layer thickness, respectively.
- The thicker the PCC overlays (i.e., from 4-inch to 6-inch), the longer the service life in reaching toward the 170 in/mile IRI performance limit.
- Increased existing asphalt pavement thickness (i.e., from 4-inch to 6-inch) may also extend concrete overlays service life.
- The IRI prediction curve for 5-inch thickness overlays on 6-inch thickness AC layer have similar service life with 6-inch thickness overlays on 4-inch thickness AC layer.

The key findings observed in Figure 2 on the 12-foot joint spacing of 5 to 6 inches thickness UBCOC are listed as follows:

- The results are similar between the 5-inch and 6-inch PCC overlays thicknesses and they are approaching the FHWA threshold around 30 years.

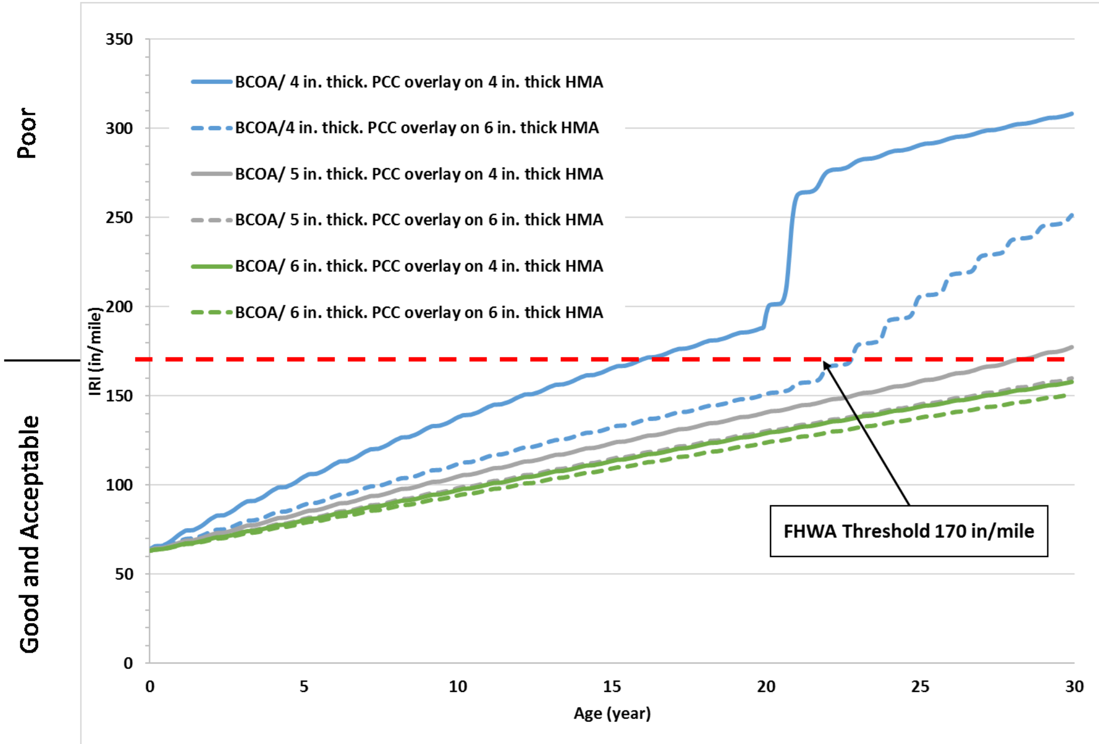


Figure 1. 12-foot joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: BCOA

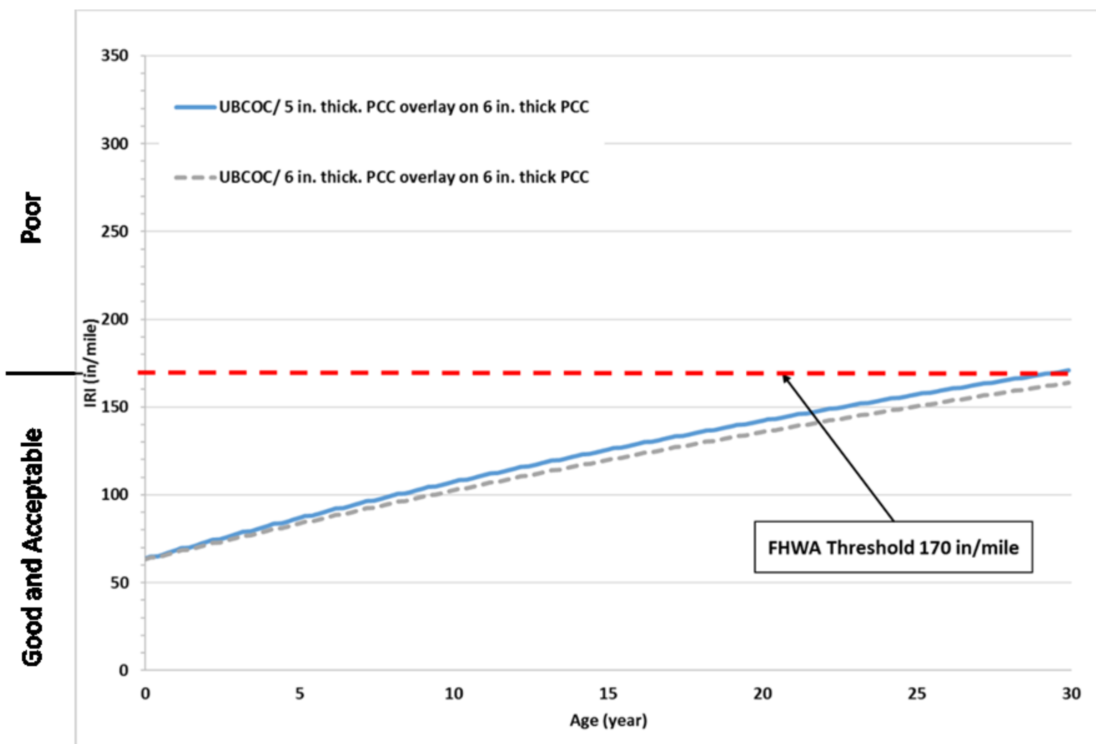


Figure 2. 12-foot joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: UBCOC

Figure 3 and Figure 4 shows Pavement ME Design IRI predictions associated with increased pavement age for BCOA and UBCOC designs with 15-foot joint spacing for each combination of overlay thickness and existing pavement thickness.

The key findings observed in Figure 3 on cases of the 15-foot joint spacing of 4 to 6 inches thickness BCOA are listed as follows:

- The IRI prediction curve for 4-inch overlays thickness increased to more than 170 in/mile after 16 years at selecting 4-inch existing AC layer thickness and after 24 years at selecting 6-inch existing AC layer thickness.
- The IRI prediction curve for 5-inch overlays thickness increased to more than 170 in/mile after 28 years at selecting 4-inch existing AC layer thickness and below 170 in/mile over the first 30 years at selecting 6-inch existing AC layer thickness.
- The IRI prediction curve for 6-inch overlays thickness were maintained at or below 170 in/mile over the first 30 years at selecting 4-inch existing AC layer thickness and at selecting 6-inch existing AC layer thickness, respectively.
- Similar to Figure 1, the thicker the PCC overlays (i.e., from 4-inch to 6-inch), the longer the service life in reaching toward the 170 in/mile IRI performance limit.
- Increased existing asphalt pavement thickness (i.e., from 4-inch to 6-inch) may also extend concrete overlays service life.
- When the existing pavement thickness is 6-in, the predicted IRI value may be due to non-related to thickness changes in concrete overlays thickness (i.e., from 5-inch to 6-inch)

The key findings observed in Figure 4 on cases of the 15-foot joint spacing of 5 to 6 inches thickness UBCOC are listed as follows:

- The results are similar between the 5-inch and 6-inch PCC overlays thicknesses and they are approaching the FHWA threshold around 30 years.

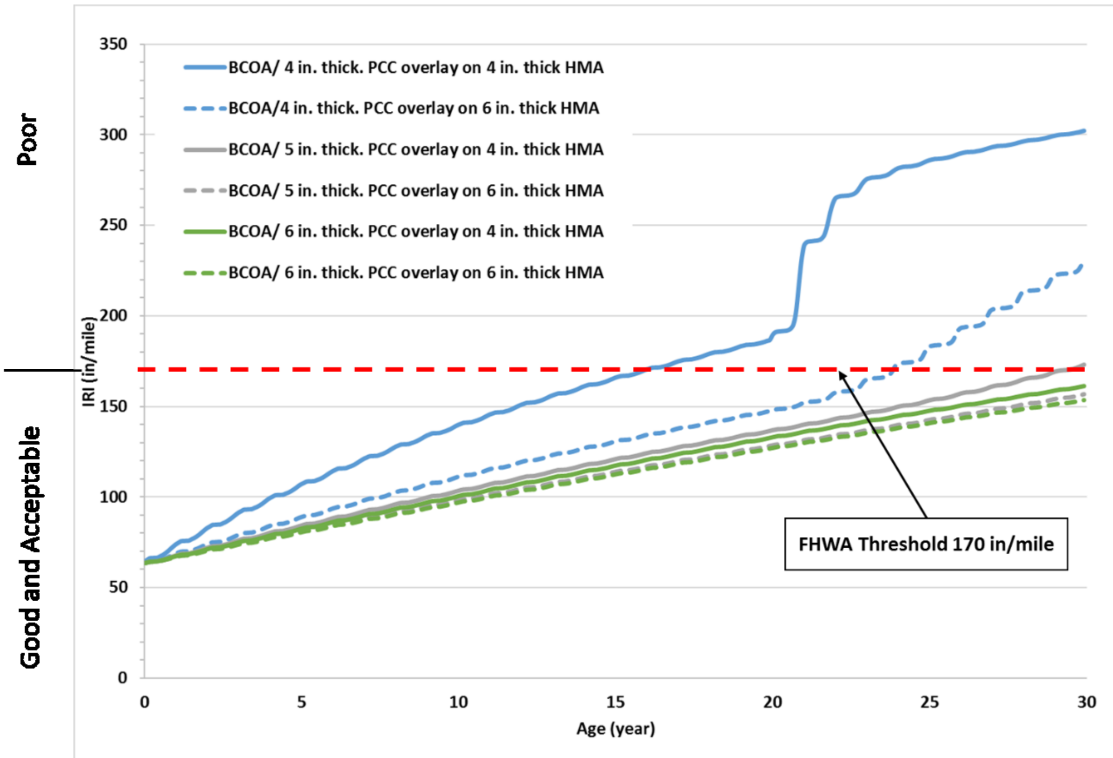


Figure 3. 15-foot joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: BCOA

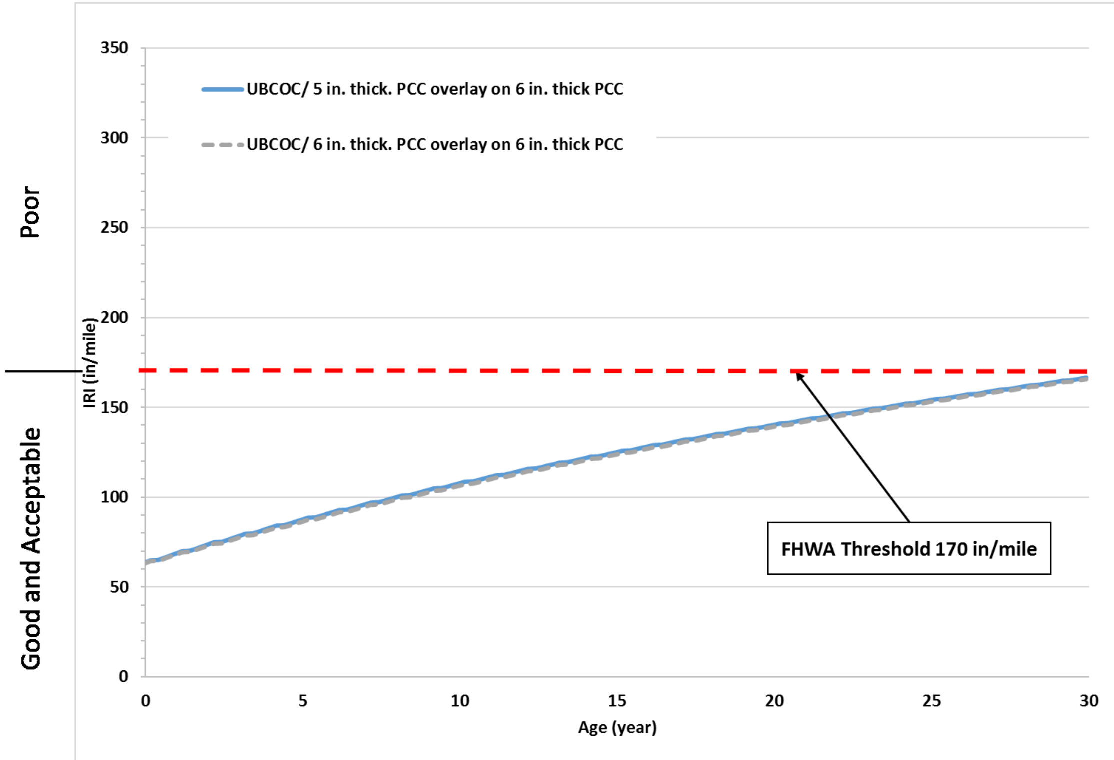


Figure 4. 15-foot joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: UBCOC

Figure 5 and Figure 6 shows Pavement ME Design IRI predictions associated with increased pavement age for BCOA and UBCOC designs with 20-foot joint spacing for each combination of overlay thickness and existing pavement thickness.

The key findings observed in Figure 5 on cases of the 20-foot joint spacing of 4 to 6 inches thickness BCOA are listed as follows:

- The IRI prediction curve for 4-inch overlays thickness increased to more than 170 in/mile after 19 years at selecting 4-inch existing AC layer thickness and after 25 years at selecting 6-inch existing AC layer thickness.
- The IRI prediction curve for 5-inch overlays thickness increased to more than 170 in/mile after 27 years at selecting 4-inch existing AC layer thickness and below 170 in/mile over the first 30 years at selecting 6-inch existing AC layer thickness.

- The IRI prediction curve for 6-inch overlays thickness were maintained at or below 170 in/mile over the first 30 years at selecting 4-inch existing AC layer thickness and at selecting 6-inch existing AC layer thickness, respectively.
- Increasing existing asphalt pavement thickness could extend concrete overlays service life.
- The joint spacing is 20-foot, the thickness of both existing pavement layer and overlays seem to have less impact on the recommended IRI performance limit.

The key findings observed in Figure 6 on cases of the 20-foot joint spacing of 5 to 6 inches thickness UBCOC are listed as follows:

- These observations indicate that the same results as for 12 and 15 feet joint spacing overlays

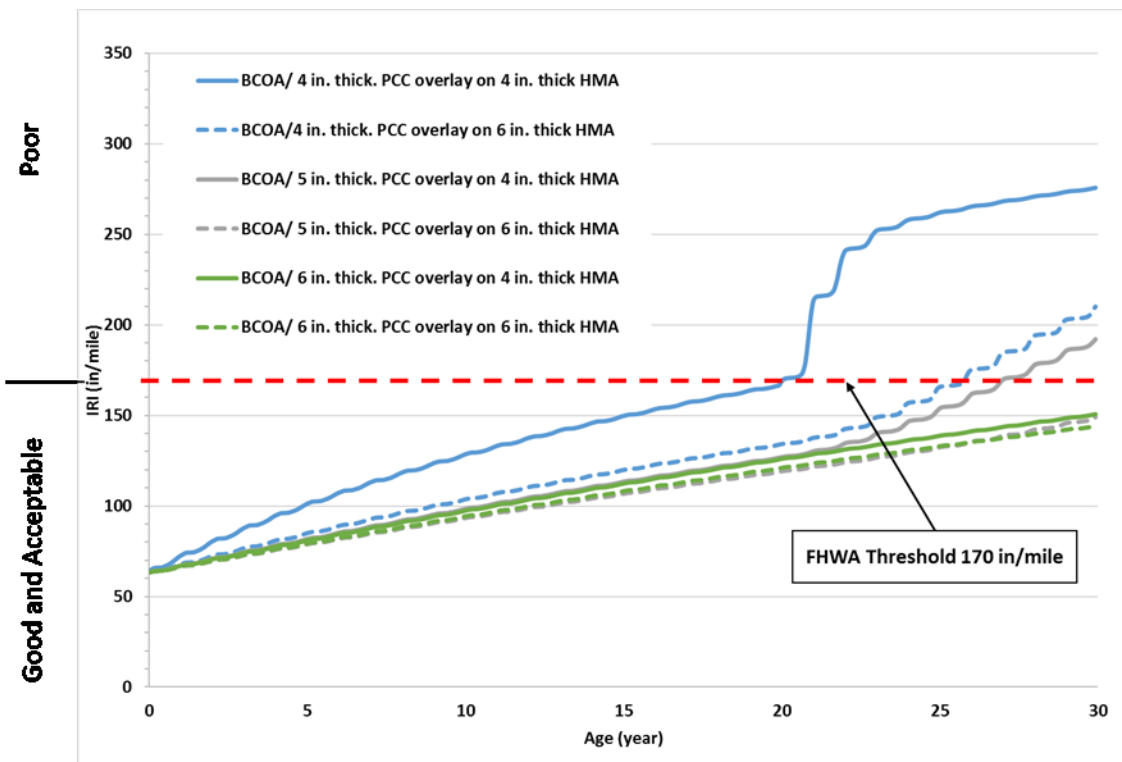


Figure 5. 20-foot joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: BCOA

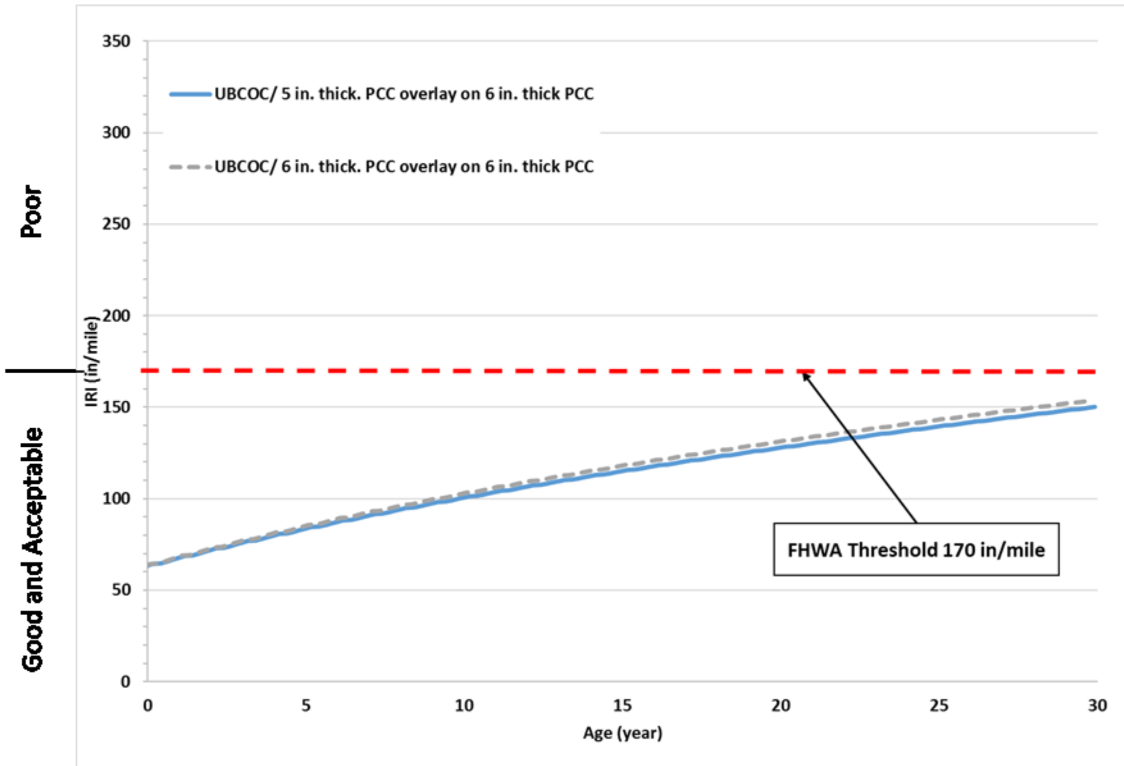


Figure 6. 20-foot joint spacing concrete overlays Pavement ME Design predicted IRI values versus age: UBCOC

BCOA-ME

From Figure 7 through Figure 9 shows how recommended thickness changes with maximum allowable percent slabs cracked for different joint spacing based on the results obtained from BCOA-ME Design software for the design of concrete overlays. Table 2 shows the structural design parameters of these concrete overlays types used in analytical investigations by using BCOA-ME Design.

Table 2. Structural design parameters of BCOA-ME design on Iowa concrete overlays projects

Design parameters	BCOA
Traffic (AADTT)	75 (ADT: 750)
Climate station	Des Moines
Existing AC/PCC layer thickness (in.)	4 and 6
HMA fatigue	Adequate
Composite Modulus of Subgrade Reaction, k-value (psi/in)	150
Does the existing HMA pavement have transverse cracks?	Yes
Fiber type and content	No fiber or 4 lb/yd^3 synthetic structural fibers
Maximum Allowable Percent Slabs Cracked (%)	5, 10, 15, 25, 50
Joint spacing (ft.)	6 × 6 12 × 12 12 × 15

As shown in Figure 7, the existing asphalt pavement was taken to be different thickness. The key findings for the concrete overlays 6-foot joint spacing projects are listed as follows:

- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (no fiber) thickness for 4-inch existing asphalt pavement is 5-inch or 4.5-inch.
- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (no fiber) thickness for 6-inch existing asphalt pavement is from 4.5-inch to 3.5-inch.

- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (with fiber) thickness for 4-inch existing asphalt pavement is 4-inch or 3.5-inch.
- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (with fiber) thickness for 6-inch existing asphalt pavement is 3-inch.

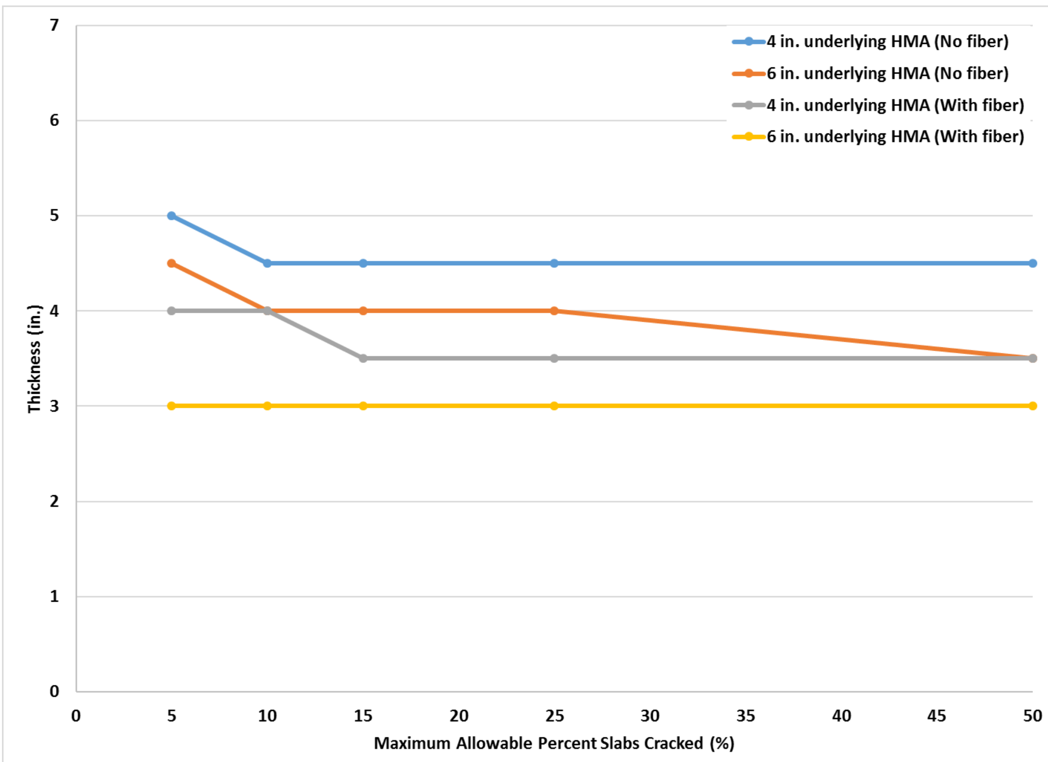


Figure 7. 6-foot joint spacing concrete overlays BCOA ME Design predicted thickness versus maximum allowable percent slabs cracked

As shown in Figure 8, the existing asphalt pavement was taken to be different thickness. The key findings for the concrete overlays 12-foot joint spacing projects are listed as follows:

- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (no fiber) thickness for 4-inch existing asphalt pavement is from 6-inch to 4.5-inch.
- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (no fiber) thickness for 6-inch existing asphalt pavement is from 5.5-inch to 4.5-inch.
- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (with fiber) thickness for 4-inch and 6-inch existing asphalt pavement is 4.5-inch.

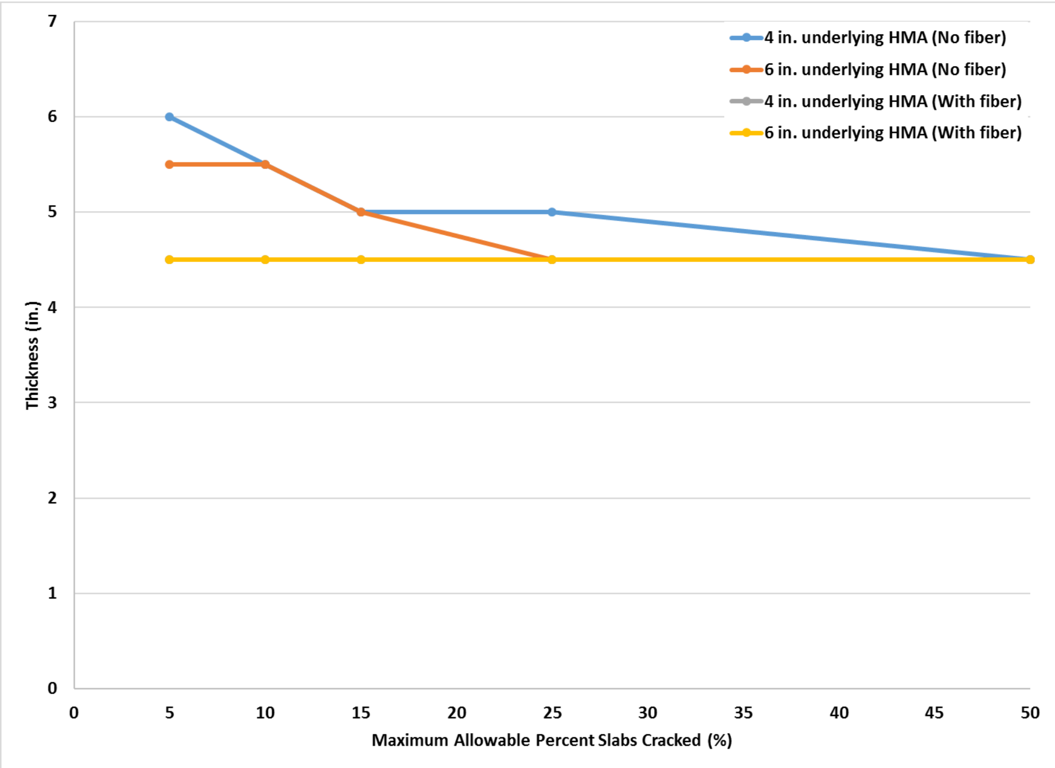


Figure 8. 12-foot joint spacing concrete overlays BCOA ME Design predicted thickness versus maximum allowable percent slabs cracked

As shown in Figure 9, the existing asphalt pavement was taken to be different thickness. The key findings for the concrete overlays 15-foot joint spacing projects are listed as follows:

- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (no fiber) thickness for 4-inch and 6-inch existing asphalt pavement is from 6.5-inch to 4.5-inch.
- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (with fiber) thickness for 4-inch existing asphalt pavement is 5-inch or 4.5-inch.
- Based on different maximum allowable percent slabs cracked, the recommended concrete overlays (with fiber) thickness for 6-inch existing asphalt pavement is 4.5-inch.

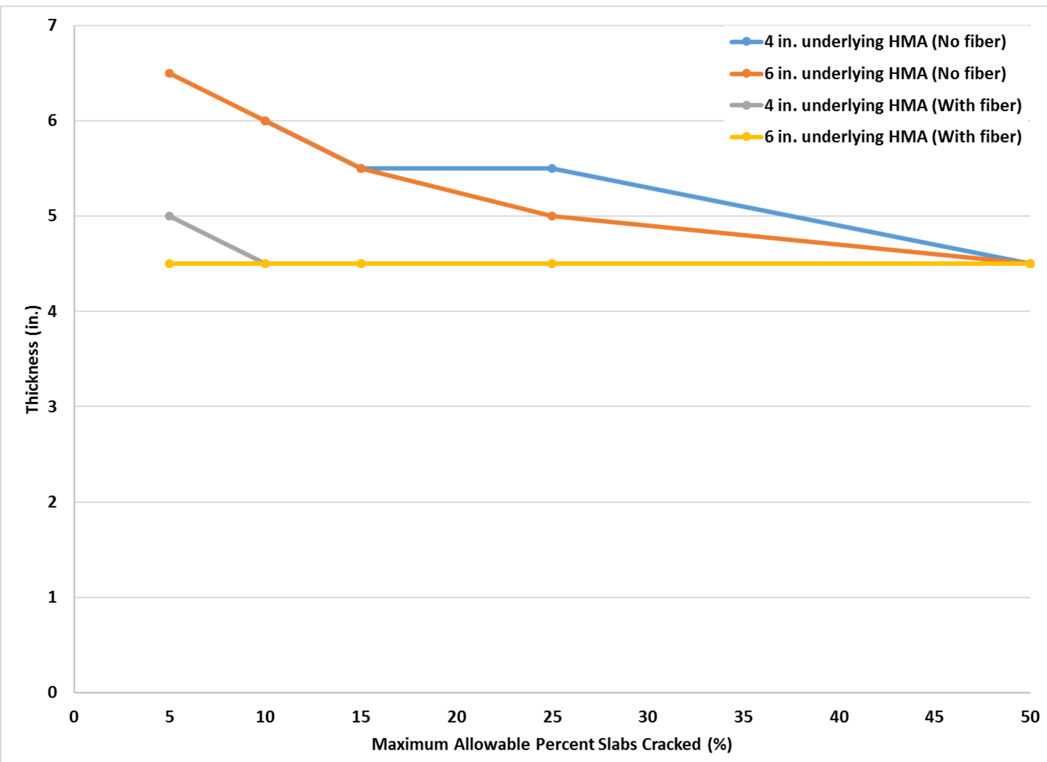


Figure 9. 15-foot joint spacing concrete overlays BCOA ME Design predicted thickness versus maximum allowable percent slabs cracked

Summary of key findings

AASHTOWare Pavement ME Design (Version 2.3.1) and BCOA-ME were used to identify effects of joint spacing and thickness on concrete overlays service life, with results providing theoretical insights. Comparison of the historical performance-related data with Pavement ME Design software results to develop recommendations on optimized joint spacing. The major findings are summarized below:

- Thicker AC existing pavement layer, and thicker PCC overlays pavement would be expected to extend the service life in accordance with the sensitivity study results produced by Pavement ME Design. Because, concrete overlays existing pavement behaves as a stable base with load-carrying capability, so the AC existing pavement thickness and condition (i.e. percentage of cracks) are critical in affecting concrete overlays service life.
- Comparing values from Figures 1 through 6, a PCC overlay structure on an existing asphalt pavement (BCOA) takes longer to reach the established IRI threshold than an existing concrete pavement (UBCOC).
- According to AASHTOWare Pavement ME Design software results, the IRI prediction curves are close to one another within large-size panel variations (12 × 12 ft., 12 × 15 ft. and 12 × 20 ft.) investigated in this study. Note that Bhattacharya et al. (2017) and Alland et al. (2018) reported that use of AASHTOWare Pavement ME Design software and BCOA-ME design procedure are mainly recommended to design BCOA with mid-size panels (e.g. 5 × 5 ft. to 8 × 8 ft.) in which the bottom-up longitudinal fatigue cracking predictions decreases significantly as the joint spacing increases.

- For a 20-foot joint spacing overlays, increasing overlays thickness shows that the IRI prediction curves are close to one another, this may be due to excessive joint spacing (20-foot) for a concrete overlay. When the thickness is 5 to 7 inches, the typical maximum transverse joint spacing design is 2 times the thickness in inches.
- Compared with Iowa historical data (refer to Concrete Overlays Performance on Iowa's Roadways field data report), Pavement ME Design 50% reliability IRI outputs are similar to Iowa concrete overlay historical data.
- From Figures 7 through 9, for overlays 4-inch and less, the maximum joint spacing is 6 feet and for overlays 4.5-inch and greater, the maximum joint spacing is 15-foot.

Results by MIRA testing

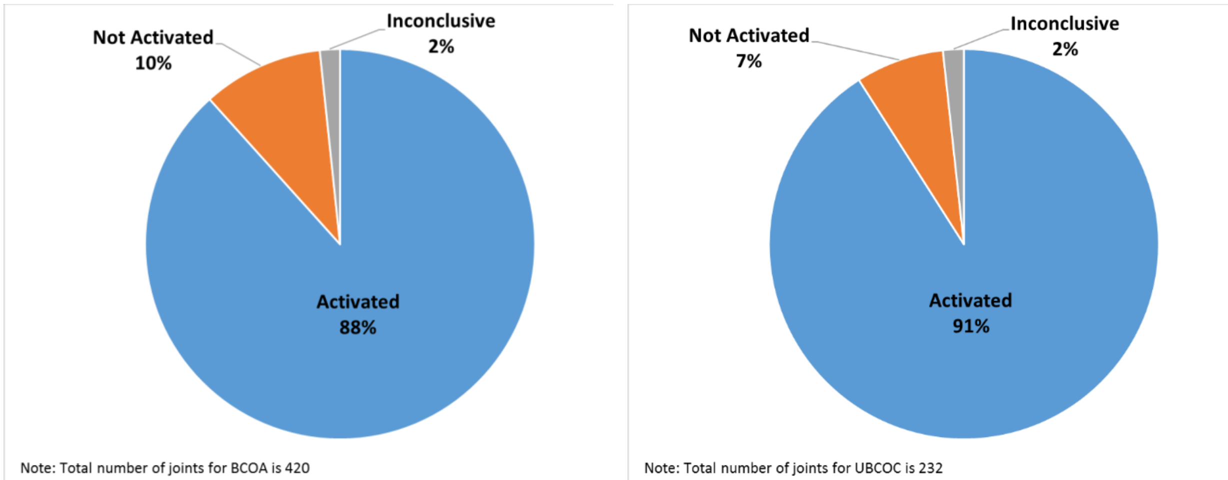
Table 3 shows the number of Iowa concrete overlays joint samples which were collected by Ultrasonic Shear-wave Tomography (MIRA) device.

Table 3. Number of MIRA testing samples on Iowa concrete overlays projects

		Number of joint samples
Types of concrete overlays	BCOA	420
	UBCOC	232
Thickness (in.)	4	87
	5	95
	6	431
	7	39
Joint spacing (ft.)	5.5 to 7.5	148
	11 to 12.5	236
	14 to 15	159
	20 to 40	109
Age (year)	0 to 5	371
	6 to 10	45
	11 to 15	93
	> 15	144
ADT	0 to 500	241
	501 to 1000	246
	1001 to 1500	83
	> 1500	112

As shown in Figure 10, the key findings for MIRA (Ultrasonic Shear-wave Tomography) testing on different types of concrete overlays joints activation are listed as follows:

- Based on MIRA testing results, BCOAs have 88% of joints were activated.
- Based on MIRA testing results, UBCOCs have 91% of joints were activated.
- Based on MIRA testing results observed joint activation did not depend or vary based on overlay type (i.e. BCOA vs. UBCOC).

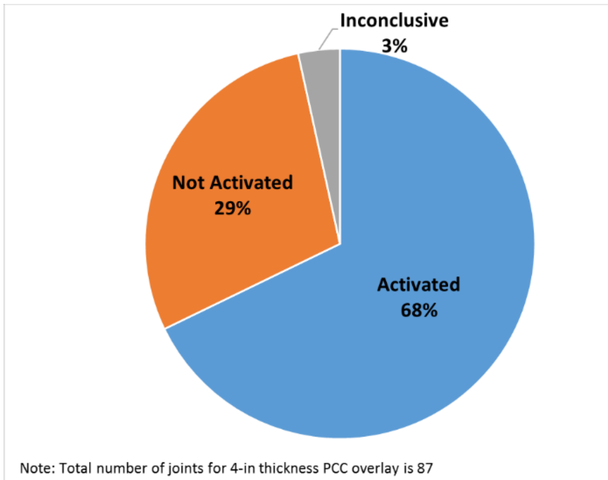


(a) BCOA (b) UBCOC

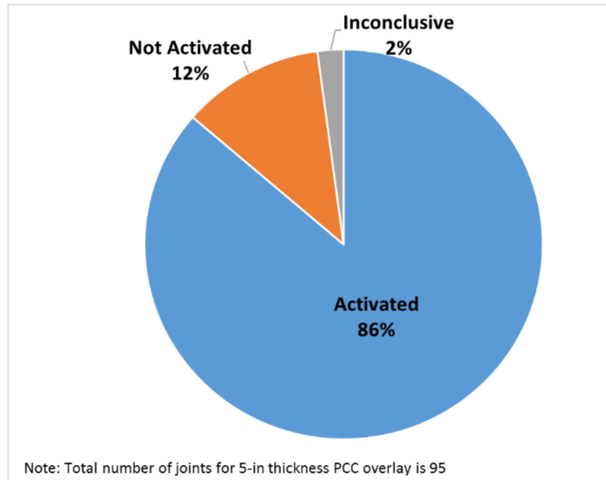
Figure 10. Percentage of joint activated for different types of concrete overlays are collected by ultrasonic testing (MIRA)

As shown in Figure 11, the key findings for MIRA testing on different thickness of concrete overlays joints activation are listed as follows:

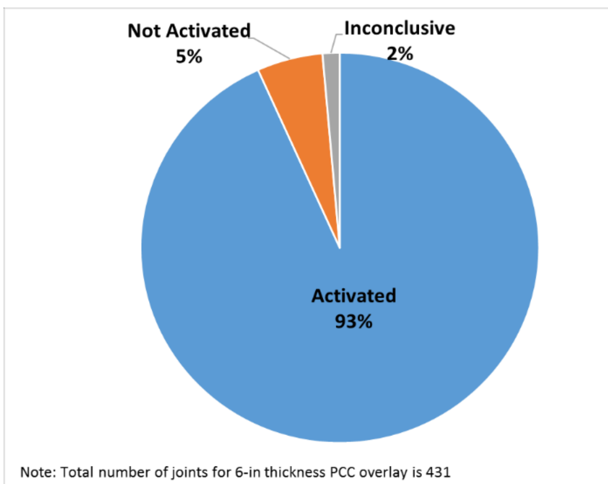
- Based on MIRA testing results, 68% of 4-inch thickness concrete overlays joints were activated.
- Based on MIRA testing results, 86% of 5-inch thickness concrete overlays joints were activated.
- Based on MIRA testing results, 93% of 6-inch thickness concrete overlays joints were activated.
- Based on MIRA testing results, 100% of 7-inch thickness concrete overlays joints were activated.
- Higher overlays thickness lead to increase the percentage of concrete overlays joint activation.



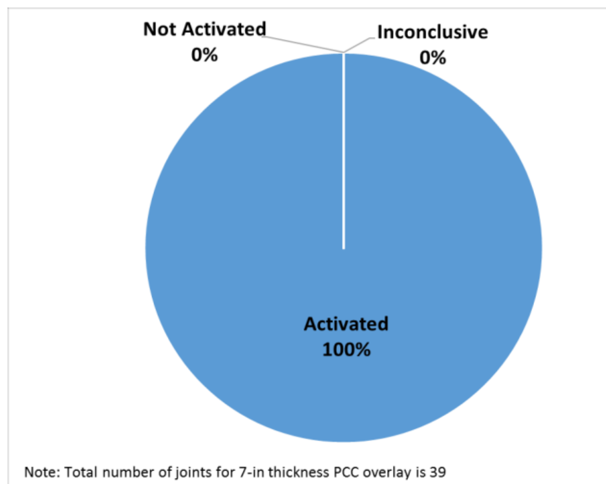
(a) 4-inch thickness



(b) 5-inch thickness



(c) 6-inch thickness



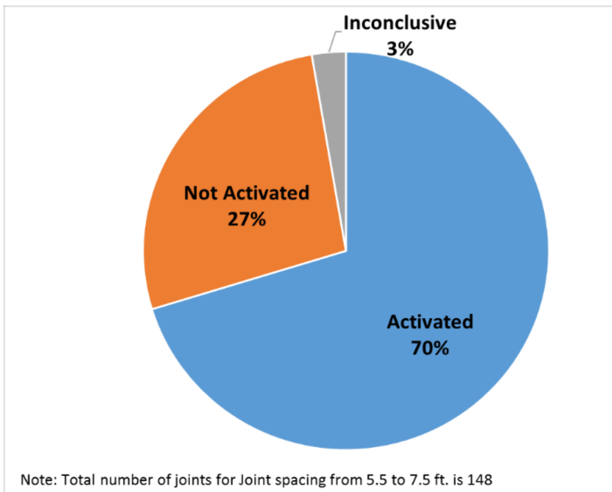
(d) 7-inch thickness

Figure 11. Percentage of joint activated for different thickness of concrete overlays are collected by ultrasonic testing (MIRA)

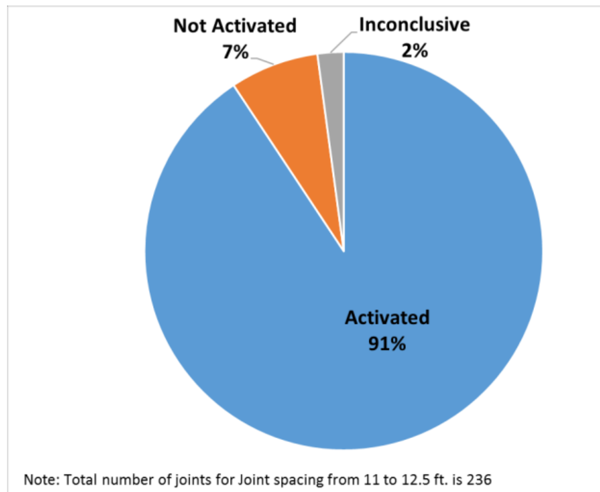
As shown in Figure 12, the key findings for MIRA testing on different joint spacing of concrete overlays joints activation are listed as follows:

- Based on MIRA testing results, 70% of 5.5-7.5-foot transverse joint spacing concrete overlays joints were activated.
- Based on MIRA testing results, 91% of 11-12.5-foot transverse joint spacing concrete overlays joints were activated.

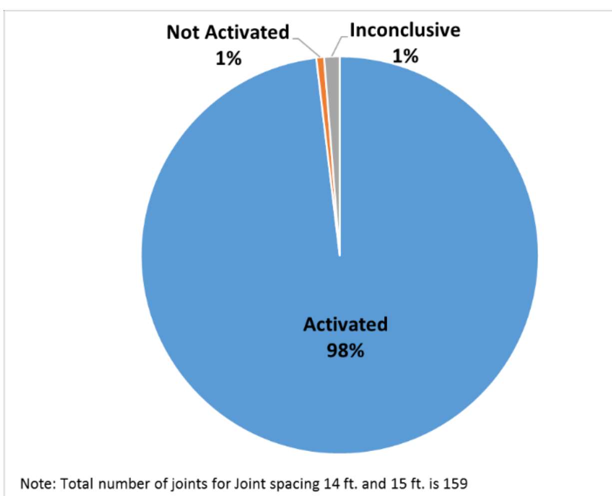
- Based on MIRA testing results, 98% of 14 and 15-foot transverse joint spacing concrete overlays joints were activated.
- Based on MIRA testing results, 99% of 20 and 40-foot transverse joint spacing concrete overlays joints were activated.
- Longer overlays joint spacing lead to increase the percentage of concrete overlays joint activation.



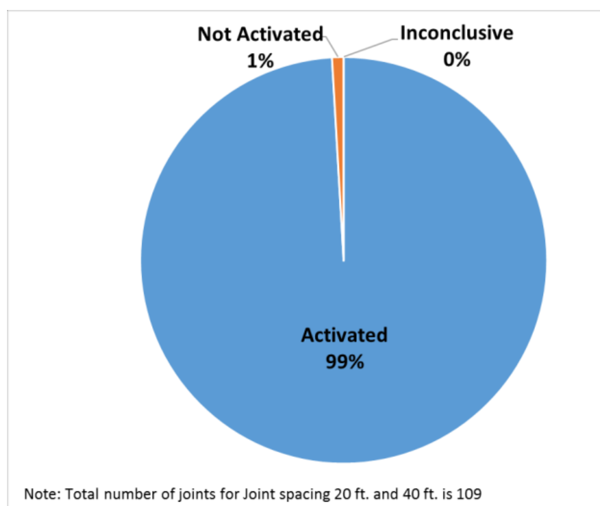
(a) 5.5 to 7.5-foot joint spacing



(b) 11 to 12.5-foot joint spacing



(c) 14 and 15-foot joint spacing

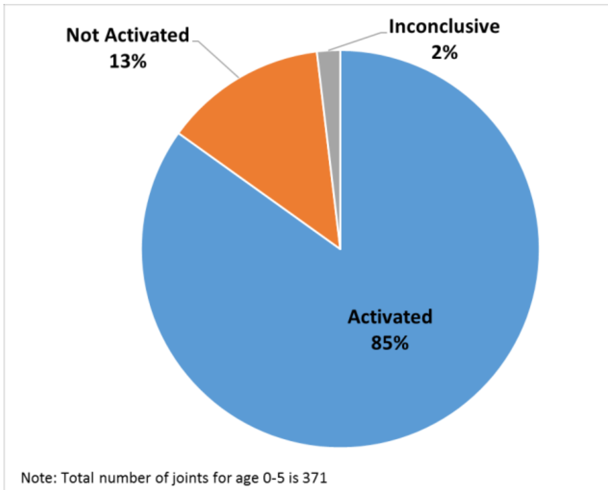


(d) 20 and 40-foot joint spacing

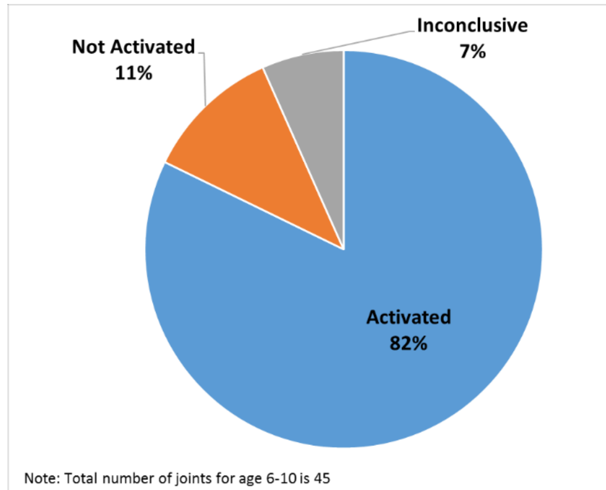
Figure 12. Percentage of joint activated for different joint spacing of concrete overlays are collected by ultrasonic testing (MIRA)

As shown in Figure 13, the key findings for MIRA testing on different age of concrete overlays joints activation are listed as follows:

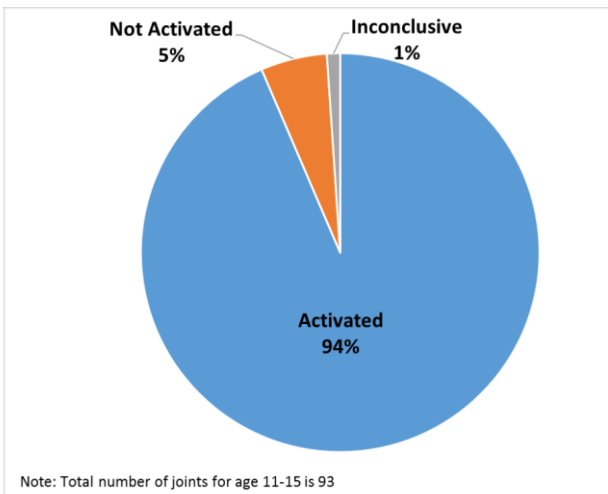
- Based on MIRA testing results, 85% of joints were activated when the concrete overlays service first 5 years of service life.
- Based on MIRA testing results, 82% of joints were activated when the concrete overlays service 6 to 10 years of service life.
- Based on MIRA testing results, 94% of joints were activated when the concrete overlays service 11 to 15 years of service life.
- Based on MIRA testing results, 100% of joints were activated when the concrete overlays service more than 15 years of service life.
- When the concrete overlays service for more than 10 years, most of the joints were activated.



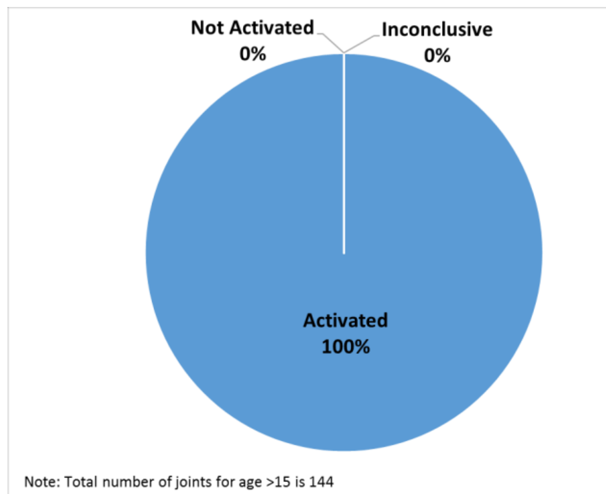
(a) 0 to 5 years old concrete overlays



(b) 6 to 10 years old concrete overlays



(c) 11 to 15 years old concrete overlays



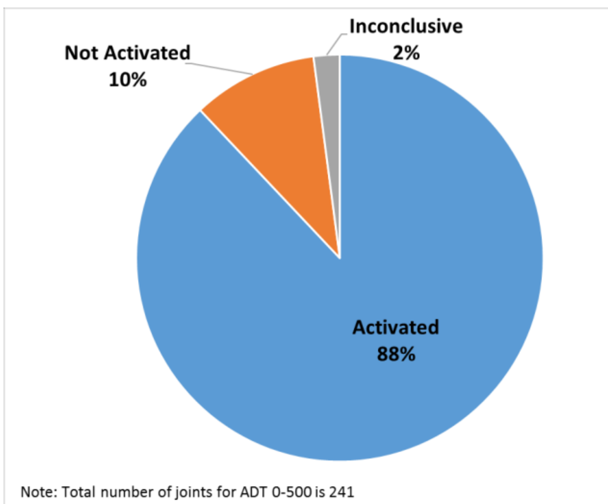
(d) more than 15 years old concrete overlays

Figure 13. Percentage of joint activated for different age of concrete overlays are collected by ultrasonic testing (MIRA)

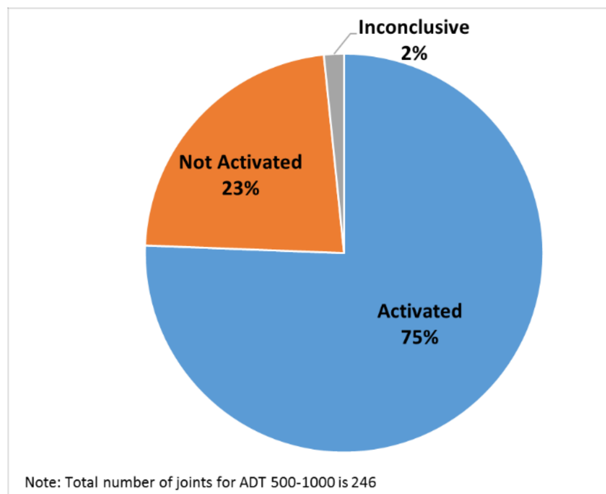
As shown in Figure 14, the key findings for MIRA testing on different traffic (ADT) of concrete overlays joints activation are listed as follows:

- Based on MIRA testing results, 88% of joints were activated when the concrete overlays pavements ADT was 0 to 500.
- Based on MIRA testing results, 75% of joints were activated when the concrete overlays pavements ADT was 501 to 1000.

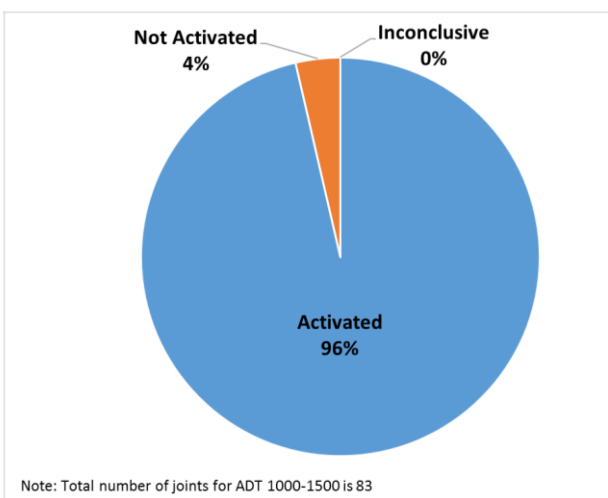
- Based on MIRA testing results, 96% of joints were activated when the concrete overlays pavements ADT was 1001 to 1500.
- Based on MIRA testing results, 93% joints were activated when the concrete overlays pavements ADT was more than 1501.
- Based on MIRA testing results observed joint activation did not depend or vary based on traffic volumes.



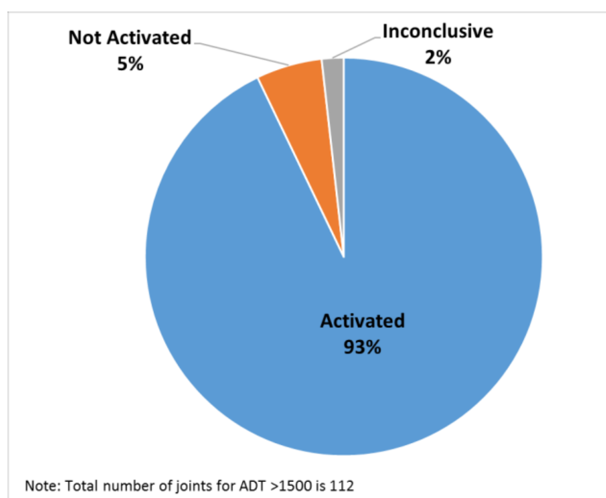
(a) ADT 0 to 500



(b) ADT 501 to 1000



(c) ADT 1001 to 1500

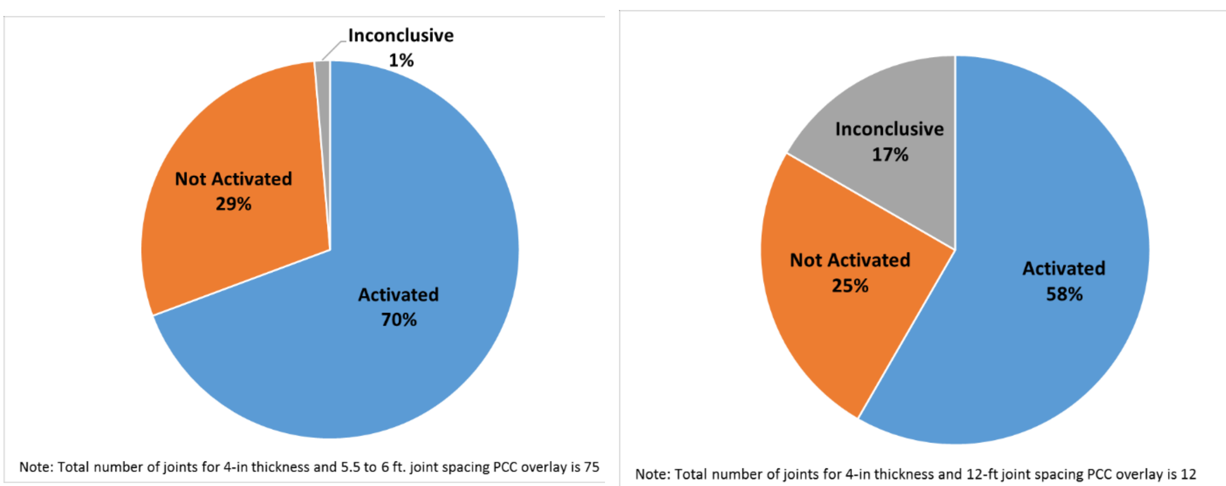


(d) ADT more than 1500

Figure 14. Percentage of joint activated for different age of concrete overlays are collected by ultrasonic testing (MIRA)

As shown in Figure 15, the key findings for MIRA testing different joint spacing of 4-in thickness of PCC overlays joints activation are listed as follows:

- Based on MIRA testing results, 70% of joints were activated when the concrete overlays pavements joint spacing was 5.5 to 6-foot.
- Based on MIRA testing results, 58% of joints were activated when the concrete overlays pavements joint spacing was 12-foot.
- Longer overlays joint spacing did not lead to increase the percentage of concrete overlays joint activation. This may be due to lack of sample size for 12-foot joint spacing of 4-inch thickness of PCC overlays.



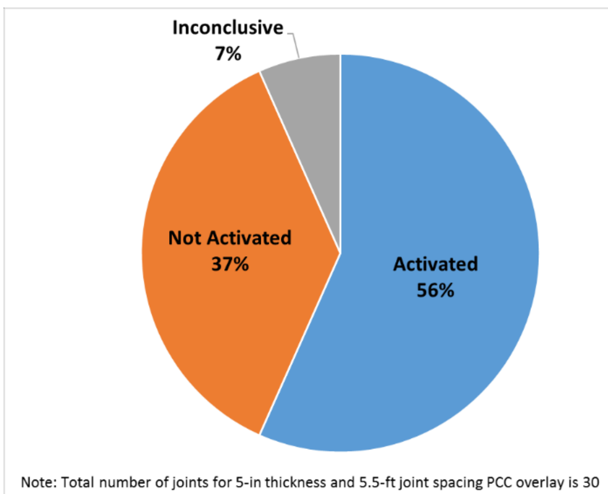
(a) 5.5 to 6-foot joint spacing (b) 12-foot joint spacing

Figure 15. Percentage of joint activated for different joint spacing of 4-inch thickness concrete overlays are collected by ultrasonic testing (MIRA)

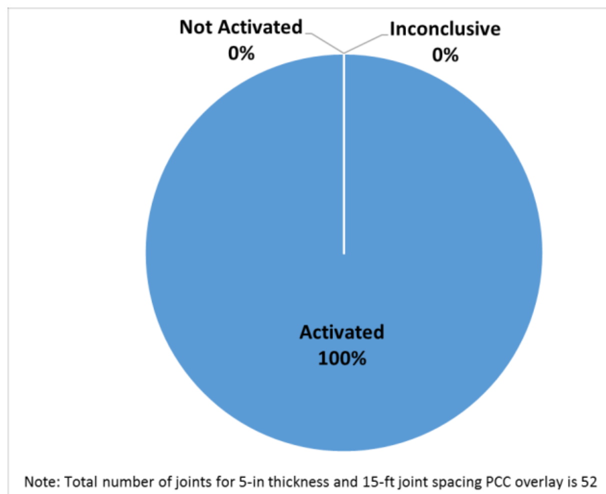
As shown in Figure 16, the key findings for MIRA testing different joint spacing of 5-in thickness concrete overlays joints activation are listed as follows:

- Based on MIRA testing results, 56% of joints were activated when the concrete overlays pavements joint spacing was 6-foot.

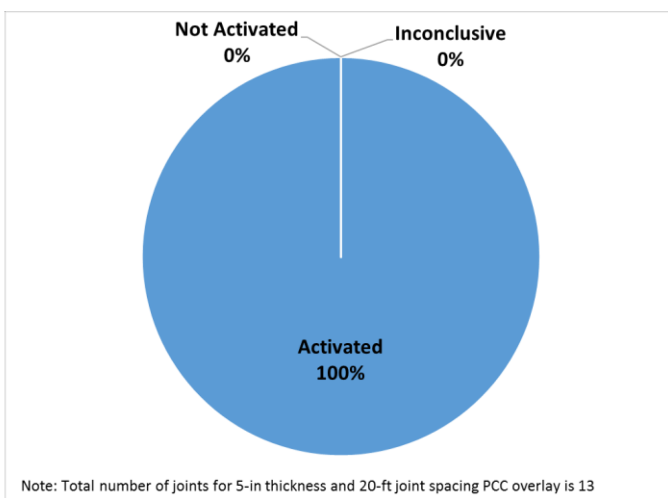
- Based on MIRA testing results, 100% of joints were activated when the concrete overlays pavements joint spacing was 12-foot.
- Based on MIRA testing results, 100% of joints were activated when the concrete overlays pavements joint spacing was 20-foot.
- Longer overlays joint spacing lead to increase the percentage of concrete overlays joint activation.



(a) 5.5-foot joint spacing



(b) 15-foot joint spacing

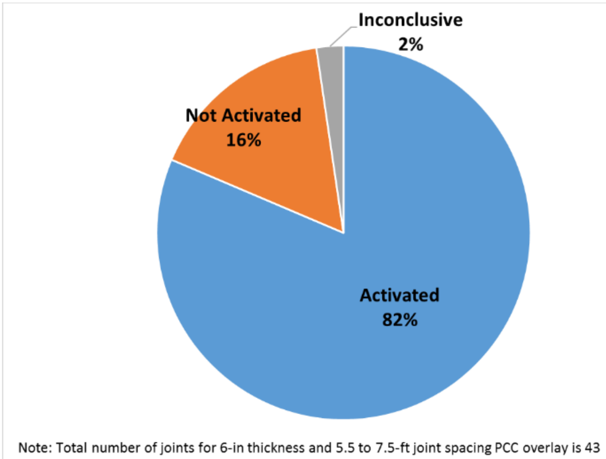


(c) 20-foot joint spacing

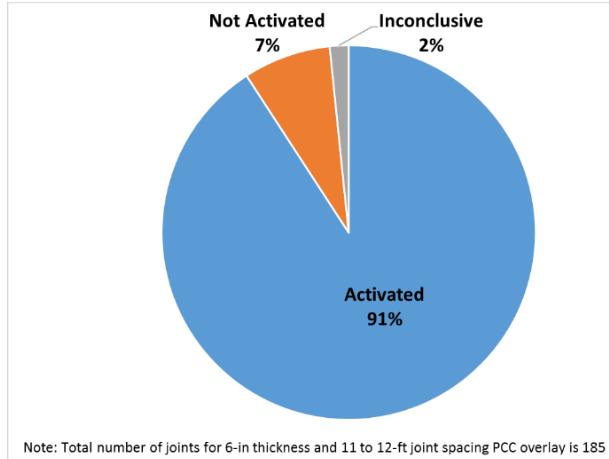
Figure 16. Percentage of joint activated for different joint spacing of 5-inch thickness concrete overlays are collected by ultrasonic testing (MIRA)

As shown in Figure 17, the key findings for MIRA testing different joint spacing of 6-in thickness concrete overlays joints activation are listed as follows:

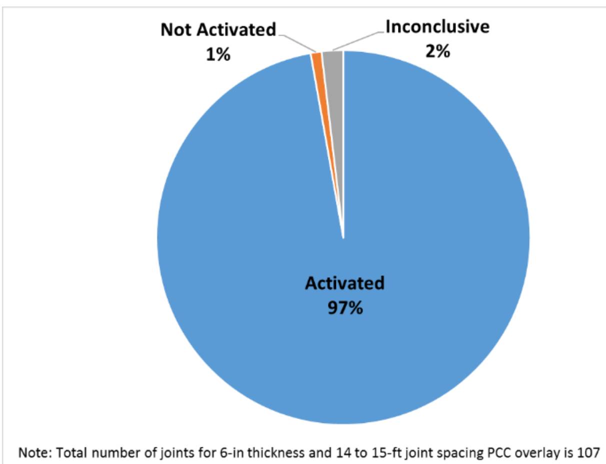
- Based on MIRA testing results, 82% of joints were activated when the concrete overlays pavements joint spacing was 5.5 to 7.5-foot.
- Based on MIRA testing results, 91% of joints were activated when the concrete overlays pavements joint spacing was 11 to 12-foot.
- Based on MIRA testing results, 97% of joints were activated when the concrete overlays pavements joint spacing was 14 to 15-foot.
- Based on MIRA testing results, 100% of joints were activated when the concrete overlays pavements joint spacing was 20-foot.
- Based on MIRA testing results, 80% of joints were activated when the concrete overlays pavements joint spacing was 40-foot. This may be due to lack of sample size, so the 40-foot joint spacing did not lead to increase the percentage of joint activation.



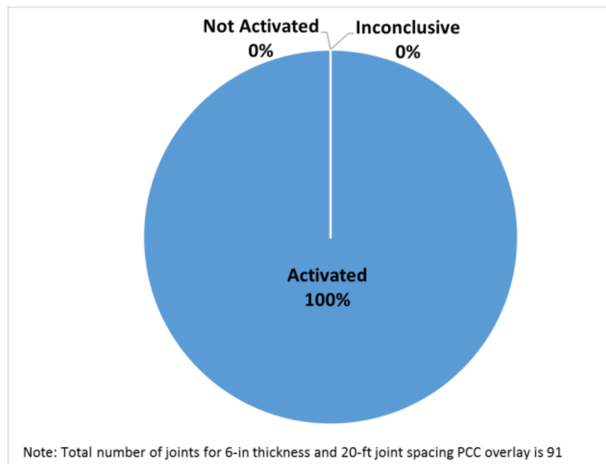
(a) 5.5 to 7.5-foot joint spacing



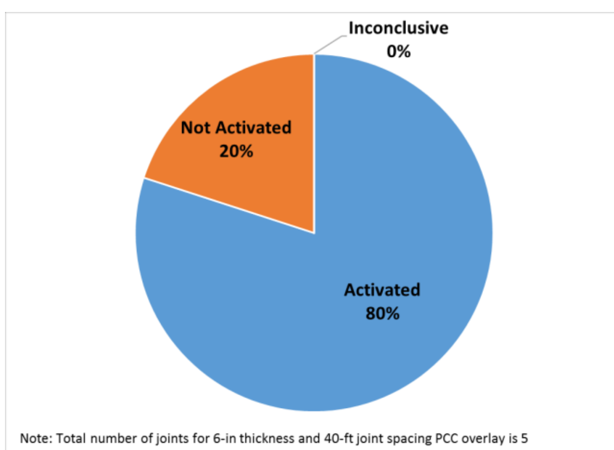
(b) 11 to 12-foot joint spacing



(c) 14 to 15-foot joint spacing



(d) 20-foot joint spacing

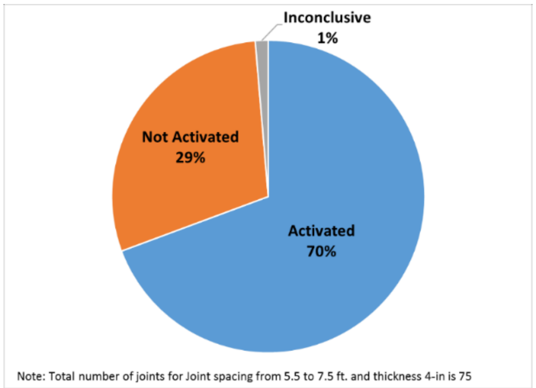


(e) 40-foot joint spacing

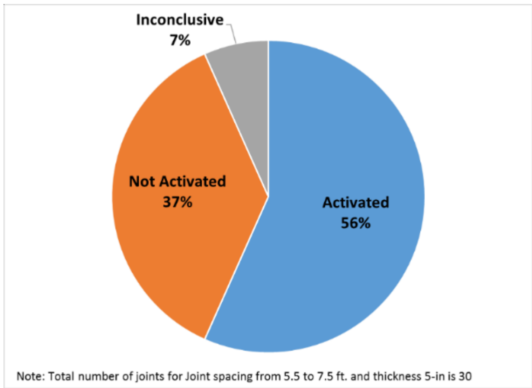
Figure 17. Percentage of joint activated for different joint spacing of 6-inch thickness concrete overlays are collected by ultrasonic testing (MIRA)

As shown in Figure 18, the key findings for MIRA testing different thickness of 5.5 to 7.5-foot joint spacing concrete overlays joints activation are listed as follows:

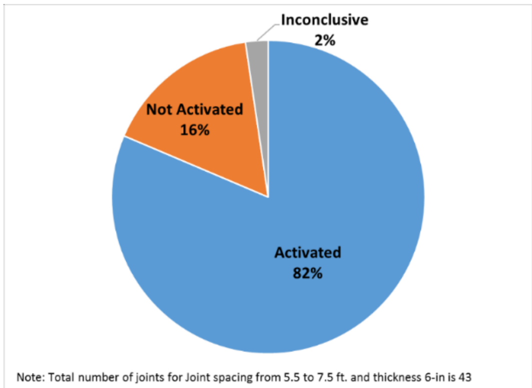
- Based on MIRA testing results, 70% of joints were activated when the concrete overlays pavements thickness was 4-inch.
- Based on MIRA testing results, 56% of joints were activated when the concrete overlays pavements thickness was 5-inch. This may be due to lack of sample size, so the 5-inch thickness did not lead to increase the percentage of joint activation.
- Based on MIRA testing results, 82% of joints were activated when the concrete overlays pavements thickness was 6-inch.



(a) 4-inch thickness



(b) 5-inch thickness

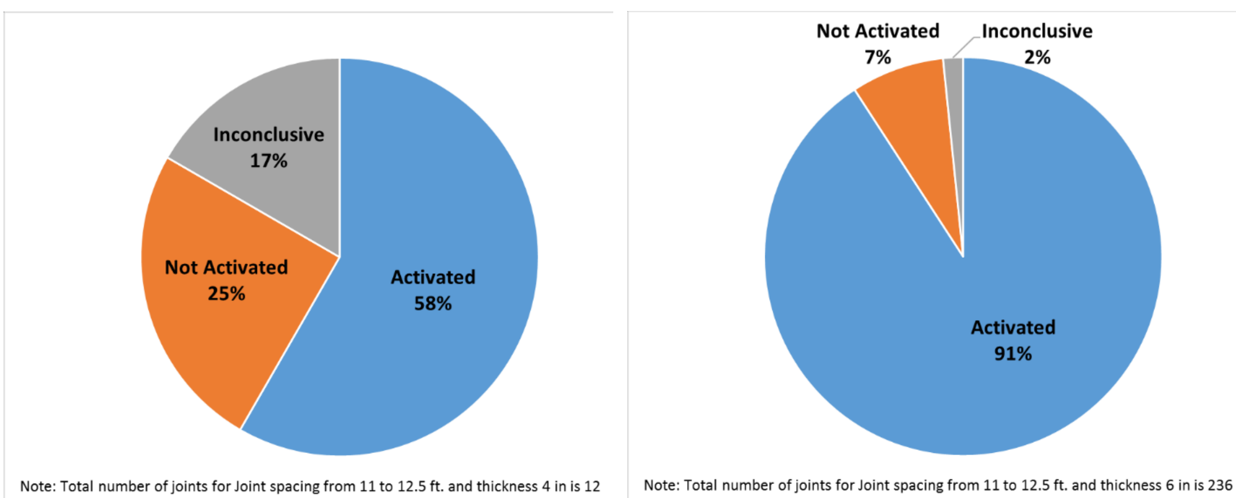


(c) 6-inch thickness

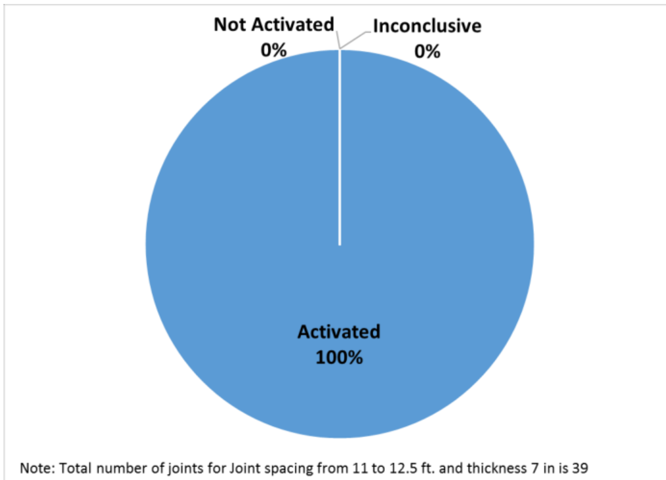
Figure 18. Percentage of joint activated for different thickness of 5.5 to 7.5-foot joint spacing concrete overlays are collected by ultrasonic testing (MIRA)

As shown in Figure 19, the key findings for MIRA testing different thickness of 11 to 12.5-foot joint spacing concrete overlays joints activation are listed as follows:

- Based on MIRA testing results, 58% of joints were activated when the concrete overlays pavements thickness was 4-inch.
- Based on MIRA testing results, 91% of joints were activated when the concrete overlays pavements thickness was 6-inch.
- Based on MIRA testing results, 100% of joints were activated when the concrete overlays pavements thickness was 7-inch.
- Higher overlays thickness lead to increase the percentage of concrete overlays joint activation.



(a) 4-inch thickness (b) 6-inch thickness

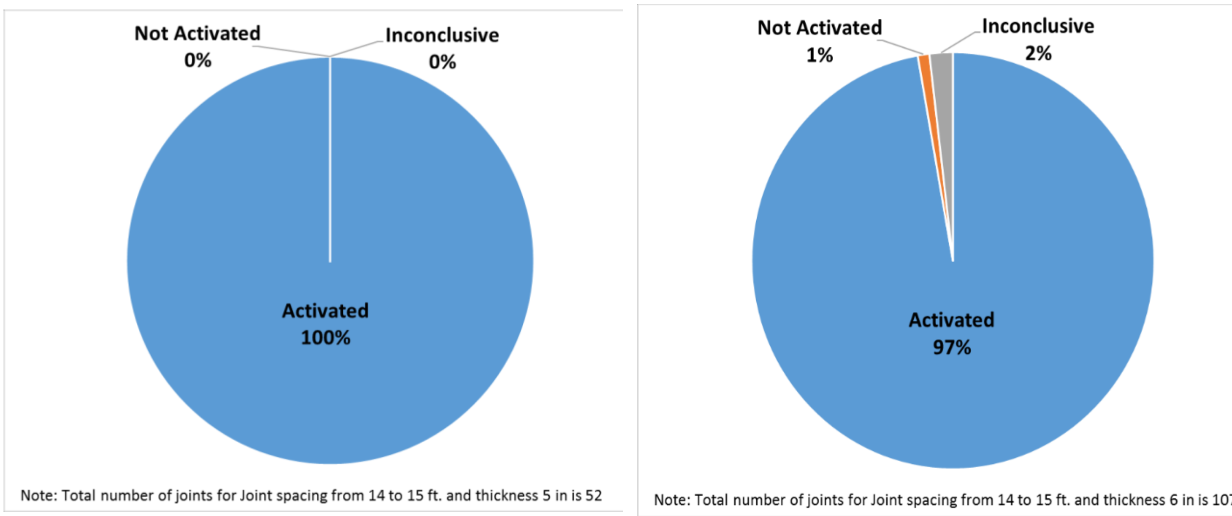


(c) 7-inch thickness

Figure 19. Percentage of joint activated for different thickness of 11 to 12.5-foot joint spacing concrete overlays are collected by ultrasonic testing (MIRA)

As shown in Figure 20, the key findings for MIRA testing different thickness of 14 to 15-foot joint spacing concrete overlays joints activation are listed as follows:

- Based on MIRA testing results, 100% of joints were activated when the concrete overlays pavements thickness was 5-inch.
- Based on MIRA testing results, 97% of joints were activated when the concrete overlays pavements thickness was 6-inch.
- When the concrete overlays joint spacing was 14-foot to 15-foot, most of the joints were activated.

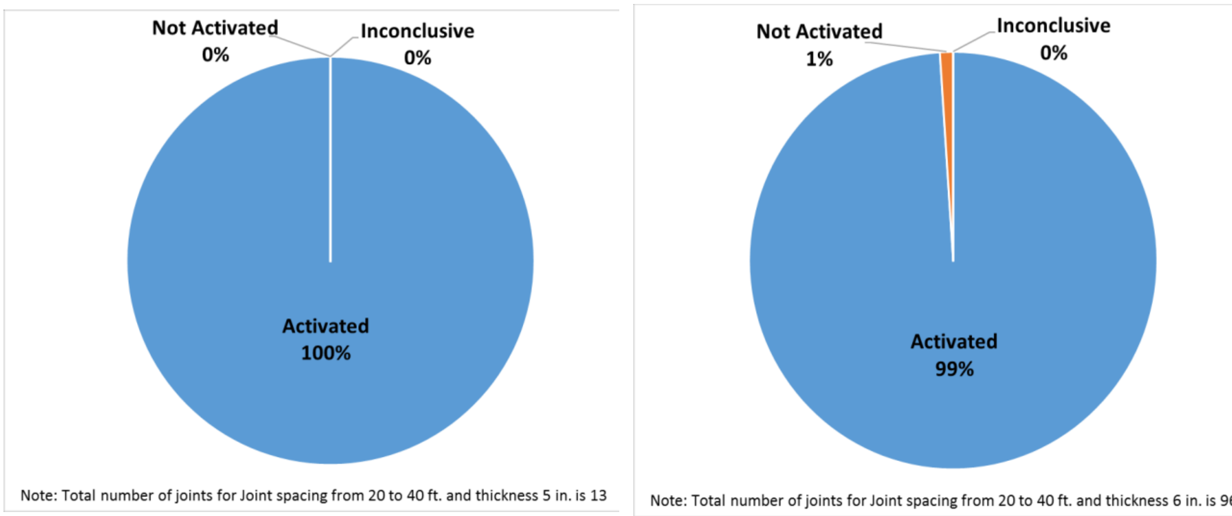


(a) 5-inch thickness (b) 6-inch thickness

Figure 20. Percentage of joint activated for different thickness of 14 to 15-foot joint spacing concrete overlays are collected by ultrasonic testing (MIRA)

As shown in Figure 21, the key findings for MIRA testing different thickness of 20 to 40-foot joint spacing concrete overlays joints activation are listed as follows:

- Based on MIRA testing results, 100% of joints were activated when the concrete overlays pavements thickness was 5-inch.
- Based on MIRA testing results, 99% of joints were activated when the concrete overlays pavements thickness was 6-inch.
- When the concrete overlays joint spacing larger than 20-foot, most of the joints were activated.



(a) 5-inch thickness (b) 6-inch thickness

Figure 21. Percentage of joint activation for different thickness of 20 to 40-foot joint spacing concrete overlays are collected by ultrasonic testing (MIRA)

Summary of key findings

MIRA (Ultrasonic Shear-wave Tomography) testing was used to identify the joints with joint activated on concrete overlays to develop recommendations on optimized joint spacing. The major findings are summarized below:

- Based on MIRA testing results observed joint activation did not depend or vary based on overlay type (i.e. BCOA vs. UBCOC).
- Higher overlays thickness lead to increase the percentage of concrete overlays joint activation.
- Longer overlays joint spacing lead to increase the percentage of concrete overlays saw joint activation.
- When the concrete overlays service for more than 10 years, most of the joints were activated.
- Joint activation did not depend or vary based on the traffic volumes.

- From Figure 15 through 17, for consistent overlays thickness, longer joint spacing of overlays still increase the apparent number of joints that are activation. (Note: There are some figures (i.e. Figure 15 (b) and 17 (e)) present that longer overlays joint spacing did not lead to increase the percentage of concrete overlays joint activation, this may be due to lack of sample sizes.)
- From Figure 18 through 21, for consistent overlays joint spacing, higher overlays thickness still increase the apparent number of joints that are activation. (Note: There are some figures (i.e. Figure 18 (b)) present that higher overlays thickness did not increase the apparent number of joints that are activation, this may be due to lack of sample sizes.)