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CRITICAL ASSESSMENT OF JOINTED PLAIN CONCRETE PAVEMENT PERFORMANCE USING 40-YEARS OF CONDITION EVALUATION DATA

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Key words: JPCP, design features, pavement life, field pavement performance data.

ABSTRACT

Georgia is considered to have one of the best concrete pavement design and materials in the U.S. Designs for joint plain concrete pavement (JPCP) have evolved over time. Analysis of long-term pavement condition data is still very necessary for evaluating the actual performance of different pavement designs and rehabilitation strategies to better understand the actual performance. Since the 1960s, various designs of jointed plain concrete pavement (JPCP), including non-doweled pavement on a soil or soil cement base (ND), non-doweled pavement on an improved base (ND-IB), and doweled pavement on an improved base (D-IB), have been constructed at different periods of time on interstate highways in Georgia with the expectation of improving pavement performance and life. This paper presents a critical assessment of long-term performance of JPCP using 40-years of pavement condition data collected by the Georgia Department of Transportation (GDOT) to quantitatively evaluate the actual performance of different JPCP designs. Pavement service life, i.e., time to reach the first major concrete pavement restoration, was analyzed using statewide data (837 survey-lane-miles of JPCPs). The service life of ND, ND-IB, and D-IB is an average of 17, 21^+ and 25^+ years, respectively, which shows a 47% improvement in the serve life of D-IB. Analyses of the traffic and distress data were conducted on selected projects. Results show all three categories of JPCP designs outperformed the designed equivalent single axle loads (ESALs), and they carried approximately two to three times the number of the designed ESALs. ND, ND-IB, and D-IB projects carried 18 million ESALs in 23 years, 22 million ESALs in 20 years, and 30 million ESALs in 33 years, respectively. In summary, the later designs have improved pavement service life, in terms of years and the accumulated ESALs, especially with the introduction of dowel bar use. In addition, the actual ESALs for all designs have exceeded the expected/design ESALs. The findings in this study reveal the actual JCCP performance and provide pavement engineers a better understanding of the long-term performance of JPCP.

I. INTRODUCTION

While many lab tests and field observations have been conducted to evaluate the performance of different jointed plain concrete pavement (JPCP) designs (Khazanovich et al., 1998; Owusu-Antwi et al., 1998; Gharaibeh and Darter, 2001, 2002, 2003; Jiang and Darter, 2005; Smith et al., 2005; Saghafi et al., 2009; Nassiri and Vandenbossche, 2012) analysis of long-term pavement condition data is still greatly needed to evaluate the actual performance of various pavement designs. Georgia is considered to have the one of the best concrete pavement design and materials in the U.S. Various JPCP designs, including non-doweled pavement on a soil or soil cement base (ND), non-doweled pavement on an improved base (ND-IB), and doweled pavement on an improved base (D-IB), have been constructed since the 1960s at different periods of time on interstate highways in Georgia with the expectation of improving pavement performance and life. GDOT conducted its first statewide condition survey for JPCPs in 1971 as part of the data collection effort for a research project to study concrete pavement faulting (Gulden, 1972). Since then, GDOT has been continuously monitoring its JPCP through its annual condition survey. This rich historical JPCP condition data provides highway agencies an excellent opportunity to evaluate the actual performance of various JPCP designs and, also, to reveal the actual behavior of different JCPC designs built in different periods of time. The research outcomes can be used to: a) to support the critical decision-making of annual maintenance, rehabilitation, and reconstruction planning and pro-

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gramming (e.g. apply individual slab replacement or reconstruction for the entire project by considering various factors, including deterioration rate, grinding cycles, economical consideration, etc.) Although most of the JPCP in U.S. is dowel JPCP now, non-dowel JPCP is still in service in U.S. and Georgia, the majority of these concrete pavements require information to support critical decisions on maintenance, rehabilitation, and reconstruction, and b) to provide crucial information to support optimal JCPC pavement designs, especially in developing countries. Again, non-dowel JPC pavements are still widely used in developing countries, especially in their secondary roadways. Thus, the information provided in this paper, including the actual pavement performance, the condition survey practices and the JPCP preservation practices will be valuable to international community, especially Georgia is considered to have the one of the best concrete pavement design and materials in the U.S.

This paper presents a critical assessment of long-term performance of different JPCP designs using 40-years of field pavement condition data collected by GDOT. This paper is organized as follows. The research need and objective are briefly described in the first section. GDOT's practices for concrete pavement design, condition survey, and restoration are presented in the second section. The data used in the analysis is presented in the third section. The fourth section presents the analyses of the performance of various JPCP designs. Conclusions and recommendations are made in the final section.

II. GDOT'S PRACTICE ON CONCRETE PAVEMENT DESIGN, CONDITION SURVEY, AND RESTORATION

1. Design for Jointed Plain Concrete Pavement

Georgia is considered to have one of the best concrete pavement design and materials in the U.S. Since the 1970s, GDOT has been actively enhancing its concrete pavement design to improve the performance and longevity of JPCP. Research and field observation were conducted to investigate the causes of faulting on Georgia's JPCP and to study the improvements for the design and the treatment methods that can effectively restore the in-service JPCP (Gulden, 1974; Gulden and Brown, 1983). GDOT developed a system (Gulden, 1972) to document the condition of every mile of JPCPR on its roadway network for quantitatively assessing the deterioration of JPCP and effectively identifying the problematic locations for study. The early research results showed that truck traffic, erodible bases, the lack of load transfer in the joints, and water intrusion through the joint were interrelated with the performance of JPCP (Gulden and Brown, 1983). Based on the findings in these studies, the design features of JPCP in Georgia have evolved through the years and various designs of JPCP have been constructed in Georgia. JPCP in Georgia can be categorized based on design features and construction time (Tsai, 2012), as described below:

- ND: non-doweled JPCP on a soil or soil cement stabilized subbase was widely used from the 1960s to early 1970s as the state-of-art design. The projects were constructed with 9-10 inches of JPCP on top of an 8-inch soil with the top 3 inches stabilized with a cutback or emulsion asphalt or 6 inch soil cement base with an asphalt shoulder (i.e., no edge support), and a 30-ft joint spacing.
- ND-IB: non-doweled JPCP with an improved base with no edge support was introduced in the early 1970s to address such issues as faulting and base erosion observed in the field. Cement stabilized Graded Aggregate Base (GAB) was used to address base erosion issue and provide good support. Along with the improvements in the subbase, a variation of joint spacing (e.g., random) and joint orientation (e.g., skewed) was also tested to address the faulting issue. An asphalt shoulder was still used.
- D-IB: doweled JPCP on an improved base, such as GAB, with edge support became the standard practice of GDOT's JPCP design in the late 1970s as a result of various research studies conducted by GDOT (Gulden, 1972). Doweled JPCP constructed between the late 1970s and 1980s often have a tied concrete shoulder to provide edge support and a better longitudinal joint for sealing out surface water. A joint spacing of 20-ft or 30-ft is typically used.

Today, GDOT's JPCP design for interstate highways and heavy truck routes consists of doweled JPCP with a 15-ft squared joint spacing and a 13-ft wide slab on top of a GAB base with a 3-inch HMA interlayer between concrete slab and GAB base. The "13-ft wide slab" is a 12-ft outside lane (as marked by the edge traffic stripe) plus 1-ft of the same slab as part of the shoulder to provide better edge support.

2. Concrete Pavement Condition Evaluation System

Georgia is, also, a state leading in applying concrete pavement restoration to extend the service life of JPCP. GDOT first conducted statewide faulting measurement of its interstate highways in 1971 as part of the data collection effort for a research project to study concrete pavement faulting (Gulden, 1972). Since then, GDOT has been conducting an annual survey on its JPCP. In 1996, a Concrete Pavement Condition Evaluation System (CPACES) was developed to standardize concrete pavement survey in terms of distress types and severity level (Tsai, 2012).

The annual survey consists of measuring joint faulting and counting pavement defect occurrences in outside lanes for each mile of JPCP in Georgia (GDOT, 1993). The faulting of every eighth joint is measured using a Georgia Faultmeter to obtain representative samples of each mile of JPCP. The Georgia Faultmeter, as shown in Fig. 1(a), was designed, developed, and built by GDOT's Office of Materials and Research in 1987 to simplify measuring JPCP joint faulting (Stone, 1991). The electronic digital faultmeter is placed on

Table 1. Type and severity of distresses in CPACES.

Distress Type	Sample Location	Severity	Report Unit
Faulting	Every 8th joint	-	Faulting Index
Broken slab	One mile	Level 1	# of slabs
		Level 2	
Longitudinal crack (Slabs with longitudinal crack)	One mile	Level 1	# of slabs
		Level 2	
Replaced slab	One mile	-	# of slabs
Failed replaced slab	One mile	-	# of slabs
Joint with spalls	One mile	-	# of joints
Joint with patched spalls	One mile	-	# of joints
Joint with failed spalls	One mile	-	# of joints
Shoulder joint distress	One mile	-	% of length
Roughness (IRI)	One mile	-	mm/km

(a) The Georgia fault meter (b) Manually measure faulting on the roadway

Fig. 1. Georgia Faultmeter.

the joint at 1 ft from the pavement marking edge to measure the difference in elevation to the nearest 1/32 inches between the pavement surfaces on either side of a transverse joint, as shown in Fig. 1(b). It reads out directly in 32nd of an inch (e.g., a digital readout of "3" indicates 3/32 inches of faulting). This accuracy was chosen because it was difficult to read the dial gages used in the original manual model to any better accuracy. The Georgia Faultmeter is the most popular hand-held device for measuring faulting and has been adopted by many state DOTs (e.g., Minnesota DOT) and the Long-term Pavement Performance (LTPP) program for measuring JPCP joint faulting. For every mile of JPCP, a faulting index that represents the total faulting of a hypothetical five joints per mile is reported. The faulting index is computed as five times the sum of all readings divided by the number of readings (Eq. (1)). A faulting index of 15 is equivalent to an average faulting of 3/32 inches (2.4 mm) in one mile.

$$F.I. = 5 * \left(\frac{\Sigma \ faulting \ reading \ of \ every \ 8th \ joint}{number \ of \ faulting \ readings} \right) \quad (1)$$

The rest of the CPACES survey consists of a visual tally of horizontally broken slabs, longitudinal cracks, replaced slabs, spalled joints, patched joints, failed spall patches, and shoulder deterioration. Table 1 summarizes the distresses included in CPACES. An annual pavement condition report is generated to summarize the distresses as well as the rating in each mile. A condition rating was developed in 1993 to provide an overall assessment of concrete pavement condition based on pavement distresses and to associate it with the maintenance and rehabilitation treatments (GDOT, 1993). Pavement roughness values, i.e., an international roughness index (IRI), are also included in this report. The roughness has been measured using different devices (Mays Ride Meter in inches per mile and Road Laser Profiler in millimeters per kilometer) in the past 40 years and requires a method to convert them to a consistent measure.

3. Concrete Pavement Restoration Strategy

GDOT has developed a concrete pavement restoration strategy through research studies and field observations. Faulting and broken slabs are primary concerns for JPCP, especially for non-doweled JPCP constructed in the 1960s and early 1970s. Diamond grinding in conjunction with base stabilization through pressure grouting, slab replacement, and joint resealing has been used as major CPR activities. A faulting index of 20 early on was designed as a trigger point for major CPR. This value is equivalent to a faulting of 1/8 inch that is used as a threshold in Mechanical Empirical Pavement Design Guide (MEPDG) (AASHTO, 2008). A faulting index of 15 was later used as a new trigger to reflect a more stringent requirement of rideability. However, pavements may be rehabilitated before reaching a faulting index of 15 or 20, depending on rehabilitation strategy and funding availability. GDOT owned and operated five diamond grinding machines in the mid 1970s and 1980s. In addition to correcting the faulting, diamond grinding alone may be applied to restore rideability (smoothness) of the pavements. Dowel bar retrofitting has not been widely used in Georgia, although the first large scale research field installations of various methods for restoring load transfer, including dowel bars, were done in Georgia in 1981 and 1982.

Table 2. JPCP treatment criteria.

Treatment	Criteria (rating and distress condition)
Grinding + reseal	[F.I. >= 15] OR [Smoothness >= 1,100]
Broken slab replacement	F.I. < 15, Smoothness < 1,100 AND No. of Severity Level 2 Broken Slab >= 10
One-mile slab replacement	No. of Severity Level 2 Broken Slab >= 1/3 of total number of slabs in one-mile.
Grinding + reseal + broken slab replacement	[F.I. >= 15 AND No. of Severity Level 2 broken Slab >= 10] OR [Smoothness >= 1,100 AND No. of Severity Level 2 Broken Slab >= 10]
Reseal	Estimated percentage of joint seal failed > 20%

Table 3. Summary of selected projects for project-level Analysis.

Project ID	Design Period (Years)	Design ESALs (Million)	Pavement Thickness	Base Type	Dowels	Joint Spacing	Shoulder Types
167	20	4.8	9"	6" Soil Cement	No	random/sk*	HMA
168	20	5.2	9"	6" Soil Cement	No	random/sk	HMA
128	20	7.3	10"	6" Cement Stabilized GAB	No	sk	HMA
129	20	10.3	10"	6" Cement Stabilized GAB	No	20', 30', sk, sq**	HMA
160	20	13.4	10"	5" Soil Cement + 1" HMA	Yes	20'sq	Tied PCC
161	20	10.4	10"	5" Soil Cement + 1" HMA	Yes	20'sq	Tied PCC

* Skewed Joint (angle to driving direction).
** Squared Joint (perpendicular to driving direction).

Table 2 shows the details of GDOT's criteria of determining JCPC maintenance and rehabilitation strategies to effectively manage GDOT's concrete pavements.

III. DATA DESCRIPTION

After data processing and screening, a total of 837 survey miles of JPCP on interstate highways in Georgia constructed between 1960 and the early 1980s was used in this study. Among them, more than half (54%) are constructed as ND; 22% are ND-IB; and 24% are D-IB. The age of the pavements ranges from 20 to 41 years with an average of 28 years. Majority of the pavements are still in service with none or some major concrete pavement restoration (CPR). The pavements are in fair to excellent condition based on the condition survey conducted in 2010. The average faulting index is about 12, and only less than 10% of JPCP have a faulting index greater than 15. While some pavements have had more than one major CPR, this paper focuses on the service life that is defined as the time to reach the first major CPR (i.e., the time between initial construction and the first major CPR).

Due to the limited availability of the detailed historic traffic data for all projects, six projects, two each in ND, ND-IB, D-IB, were selected for the project-level analysis to reveal the detailed performance of different design features. All six projects have a service life within a reasonable range of the expected service life for their design category, not extremely long or short. Detailed information, including accumulated ESALs, pavement thickness, joint spacing, base type, and design ESALs, was obtained for the project-level analysis. Table 3 summarizes the design information for each project.

IV. ANALYSIS OF 40-YEARS OF PAVEMENT CONDITION EVALUATION DATA

Two analyses were conducted to quantitatively evaluate the actual performance of different JPCP designs (ND, ND-IB, and D-IB) based on 40-years of pavement condition data collected by GDOT. First, pavement service life was analyzed by different designs using statewide data (a total of 837 surveyed miles of JPCP). Second, analyses of traffic and distresses were conducted on six selected projects with different designs to study their performance in terms of traffic carried and distresses mitigated.

1. Service Life Analysis Using Statewide Data

The service life, i.e., the time to reach the first major CPR, was determined for the 837 surveyed miles of JPCP. Fig. 2 shows the distribution of the service life by year along with the faulting index before CPR. Fig. 2 shows a broad service life ranging from 10 years to 29 years. More than 50% of the pavements are rehabilitated between 12 and 20 years. The faulting index before the CPR also varies from 9 to 24 without a particular pattern. This indicates the timing of CPR depends not only on pavement condition but also other factors, such as funding availability, adding lane(s), etc. Therefore, the time to

Table 4. Service life for the original pavement by design.

Description		ND	ND-IB	D-IB
Service Life based on actual time to reach CPR	Average	17	21$^+$	25$^+$
	Minimum	10	14	25
	Maximum	29	29	33
	FI before CPR	16.8	14.9	-
Service Life based on time to reach FI 15	Average	14	26	-
	Minimum	5	12	-
	Maximum	29	30	-

$^+$Some pavements have had yet reached a CPR. Therefore, the expected service life can be longer than the number reported.

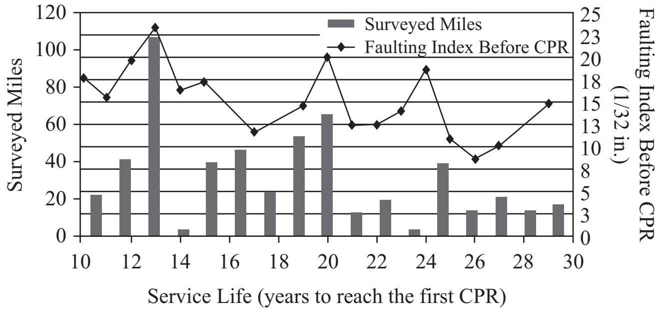


Fig. 2. Distribution of service life with faulting index before the CPR.

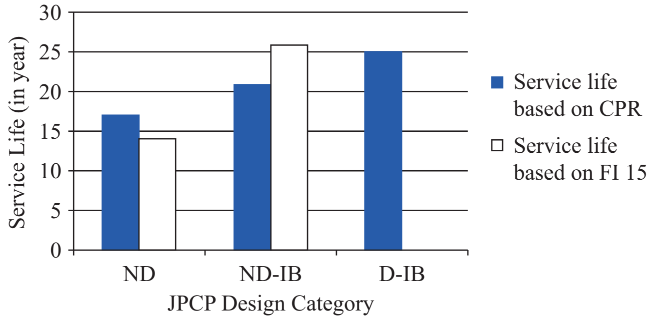


Fig. 3. Service lives of different design categories.

reach a faulting index of 15 is also used in this study to provide an objective comparison among projects.

The service life for each design category of the total of 837 surveyed miles of JPCP is summarized in Table 4. Among them, the 440 surveyed miles of ND constructed between the 1960s and early 1970s had already reached the end of service life (i.e., have had at least one major CPR) by 2010. The average service life of ND based on time to reach CPR is 17 years, shorter than the 20-year design period. The faulting index before a major CPR is 16.8, an increase of faulting at an average rate of approximately 1 faulting index per year. The service life based on a faulting index of 15 is approximately 14 years, shorter than the one based on CPR. Also, the deterioration in the faulting index varies greatly among the 440 surveyed miles of ND.

The 183 surveyed miles of ND-IB constructed in the 1970s have an average service life of 21$^+$ years (based on CPR), which is 23% longer than that of ND pavements. The faulting index before major CPR is about 12, lower than a faulting index of 15 or 20 as used in the MEPDG default. The service life based on a faulting index of 15 is approximately 26 years, which is 83% longer than that of ND pavements (14 years). This indicates ND-IB has substantially mitigated the faulting issue. It is noted the IRI before the CPR is high, but only limited broken slabs were recorded before the CPR activities.

A total of 214 survey miles of D-IB were constructed in the late 1970s through the early 1980s. With an age ranging from 25 to 33 years, none have had a major CPR. While a service life for this design category has not been reached, it is expected to be longer than 25 years, which is, as a minimum, 47% longer than that of ND. The service life based on a faulting index of 15 was not derived due to the very slow deterioration rate in the faulting.

In summary, different JPCP designs (ND, ND-IB, and D-IB) have been applied and constructed at different periods of time in Georgia with the expectation of improving pavement life and performance. Results show that the pavement lives based on time to reach the first CPR are increasing with a later design, and they are approximately 17, 21$^+$, and 25$^+$ years of life for ND, ND-IB, and D-IB, respectively, as shown in Fig. 3. The derived lives can be used to conduct a more reliable LCCA analysis. In addition, results also show that the pavement lives (at a consistent measure with a faulting of 15) are also increasing with a better and later design. The service life of ND and ND-IB is approximately 14 and 26 years, respectively. The later designs have resulted in better performance in term of faulting. The performance with the accumulated ESALs is further analyzed based on the selected projects in the following section.

2. Traffic and Distress Analysis Using Selected Projects

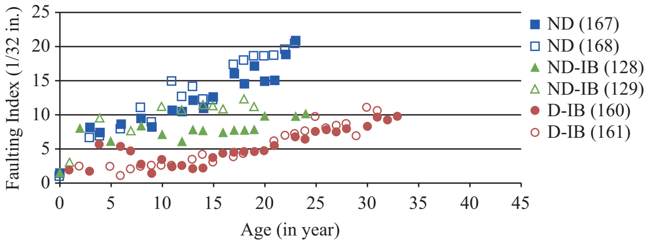
Project-level analysis, including traffic and distresses data, was conducted on six projects, two each in ND, ND-IB, and D-IB, to reveal the detailed performance for different design features. While the results of this analysis are not to be considered conclusive because of the small sample size, the information can provide a better understanding of the actual performance of JPCP with different designs, which is useful for improving pavement design.

1) ND JPCP built from 1960s to 1970s

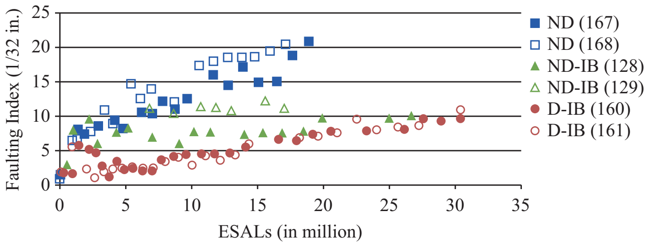
Projects 167 and 168, constructed with ND on a 6-inch soil cement base, lasted 23 years before the first major CPR. Both projects reached a faulting index of 20 and carried roughly 20 million ESALs, which is 3 times the designed ESALs, in the first 23 years before the first major CPR. The deterioration rate in the faulting index is 0.9 per year and 1.1 per million ESALs, as shown in Table 6 and Table 7. Fig. 4 shows the plots of the faulting index versus age, cumulative ESALs, and design ESALs. The deterioration in the faulting index for ND, in terms of year and ESLAs, is higher than that of ND-IB and

Table 5. Project-level analysis – before the first major CPR.

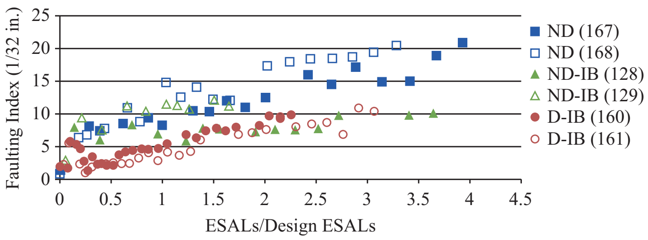
Design Category	Project	Design ESAL	Service Life		Faulting Index	Deterioration Rate Faulting Index/Year or ESAL or Design ESAL		Performance Index Sum (Faulting * Year)/ Sum (Year)	
			by Year (years)	by ESAL (10^6)		by Year (FI/Year)	by ESAL (FI/10^6 ESAL)	by Year (FI/Year)	by ESAL (FI/10^6 ESAL)
ND	167	4.8	23	18.9	20.9	0.91	1.10	14.3	14.8
ND	168	5.2	23	17.1	20.4	0.89	1.19	15.9	16.5
ND-IB	128	7.3	26	26.6	10.2	0.39	0.38	8.3	8.5
ND-IB	129	10.3	19	17.0	11.3	0.59	0.66	11.0	11.1
D-IB	160	13.4	33	30.4	9.7	0.29	0.32	6.2	6.8
D-IB	161	10.4	31	33.6	10.5	0.34	0.31	6.4	7.0



(a) Faulting index *vs*. age



(b) Faulting index *vs*. ESAL



(c) Faulting Index *vs*. design ESAL

Fig. 4. Faulting index by age, ESAL, and design ESAL.

D-IB. However, the cumulative ESALs have exceeded the design ESALs upon which the pavement thickness and design features are based. The pavements carried approximately 3.5 times the designed ESALs before the first major CPR. Overall, these two projects carried more than 3 times the designed ESALs for each project before the first major CPR with significant faulting developed in 20 years.

2) ND-IB JPCP built in the early 1970s

Projects 128 and 129, constructed with ND-IB (a 6-inch cement stabilized GAB), lasted 19 and 26 years before the first major CPR. However, the major CPR was conducted when the faulting index was roughly 10. Project 128 carried 26 million ESALs (3.5 times the designed ESALs) over 26 years; Project 129 carried 19 million ESALs (1.6 times the designed ESALs) in 17 years, as shown in Table 5. Both projects have a deterioration rate in the faulting index of less than 0.6 per year and 0.7 per million ESALs. Fig. 4. shows the faulting index deteriorates at a very slow rate in both time and ESALs, especially for Project 128.

3) D-IB JPCP built in the late 1970s

Projects 160 and 161 were constructed with D-IB (1-inch HMA interlayer and 5-inch soil cement base). Both projects have carried more than 30 million ESALs, which is about 2.7 times the designed ESALs, over 30 years without a major CPR. They are still in fairly good condition with a faulting index of approximately 10. These two projects have a steady, low deterioration rate in the faulting index of 0.3 per year and 0.3 per million ESALs. The service lives of these two projects are expected to be more than 40 years if a faulting index of 15 is the end of service life for triggering the first CPR.

V. CONCLUSIONS AND RECOMMENDATIONS

Field pavement performance data is greatly needed to evaluate the actual performance of different pavement designs and rehabilitation strategies to improve our understanding the actual pavement behavior. GDOT has been continuously monitoring its JPCP through its annual condition survey since 1971. This rich historical JPCP condition data provides highway agencies an excellent opportunity to evaluate the actual performance of various JPCP designs and, also, to reveal the actual behavior of different JPCP designs built in different periods of time. The derived outcomes will also be useful for transportation agencies to develop a reliable pavement management, especially the decision-making on the right timing for pavement maintenance, rehabilitation, and reconstruction of JPCP. In this study, 40-years of concrete pavement condition data collected by GDOT were used to study the actual performance of various JPCP designs.

JPCPs are grouped into three categories: ND, ND-IB, and D-IB based on their design features and periods of construction. Pavement life, i.e., time to reach the first major CPR, is studied based on statewide data (837 survey miles of JPCP). In addition, the performances, in terms of the service life and accumulated ESALs, are studied on six selected projects with detailed traffic load data. Although the projects are limited, the derived information provides a better understanding of the actual performance in terms of load carrying capacity. It should also be noted that projects with the state of the art design features (i.e., 15-ft joint spacing and 13-ft wide lane on top of a GAB base), currently used by GDOT, are not included in this study because the data is limited due to their being new construction. The following summarizes the findings of the performance on different designs.

- Based on pavement life analysis using statewide data, the following summarizes the findings:
  - Results show the performance of JPCP has been improved through the changes in the design features (from ND, ND-IB to D-IB). The service life of ND, ND-IB, and D-IB based on the first major CPR is 17, 21^+, and 25^+ years, respectively. Compared to ND, the service life of D-IB increases by 47%.
  - Results of the service life based on a faulting index of 15 show a significant improvement in terms of faulting from ND to ND-IB. The average service life of ND-IB is 26 years, which is 86% longer than that of ND pavements (14 years). A longer service life of D-IB is expected because of the low deterioration rate in the faulting index.
- Based on the project-level analysis, including traffic and service life, on selected projects, the following summarizes the findings:
  - JPCPs in three designs categories outperformed the designed ESALS, carrying 2-3 times the designed ESALs before the first major CPR.
  - The deterioration rate of faulting is a) 0.9 per year or 1.1 per million ESALs for ND, b) less than 0.6 per year and 0.7 per million ESALs for ND-IB, and c) 0.3 per year and 0.3 per million ESALs for D-IB. Results show that dowels for load transfer can effectively reduce faulting.

Further research is recommended as follows:

- LCCA is recommended to quantitatively evaluate the economical performance of different JPCP designs.
- An economic analysis, such as LCCA, is recommended to study the cost-effectiveness of different CPRs. For instance, evaluate the cost-effectiveness of continuing CPR and reconstruction. In addition, the timing and pavement condition criteria for reconstruction should be studied.
- Limited by resources and traffic, a manual survey can only collect sampled faulting data, i.e., on every 8th joint and limited crack information. Automated data collection using a mobile 3D laser sensing system is recommended for use to improve the data collection productivity, to have full lane coverage, and to enhance the data quality in terms of accuracy and consistency. For instance, faulting on all joints and the lengths of the cracks can be collected to establish a slab-based concrete pavement management system (e.g. slab-based maintenance programming).

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