

Impact of Materials and Construction Variability on the Performance of Pavements

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Abstract

Significant variability exists in everything associated with pavements but in particular, materials and construction (M&C) factors. Major sources include (1) variability along the project in layer thickness, initial smoothness, strength, dowel placement, etc., and (2) the difference between what is specified or designed and what is actually constructed in the field. Variation causes localized areas of the pavement to be “weaker” than other areas and these areas fail first either from structural deficiencies or disintegration from durability deficiencies and either results in “early” failures requiring maintenance repairs and “early” rehabilitation of the project. The project then experiences increased life cycle costs and often additional safety risks over time. The importance of variation reduction is recognized in all areas of manufacturing and construction as a critical activity to reduce failure, improve product performance, and lower future maintenance and rehabilitation costs. This paper describes types of concrete pavement variability, its effects, and illustrates how variability reduction leads to longer pavement life.

Research Significance

Everything associated with pavements are variable or uncertain. This is particularly true for materials and construction (M&C) aspects of pavements. Gaining a better understanding of the actual impact of variability on performance, service life, maintenance and rehabilitation, and life cycle costs would lead to more significant ways to reduce variability. This paper demonstrates the impact of variability of a few M&C factors on pavement performance and service life that was part of a broader study that included life cycle cost reduction. (Darter, et al. 2009)

Description of the Variation Problem

Variability in the manufacturing or construction process and in material properties has long been viewed as a major issue that stands in the way of desired performance and reliability. Bill Motley, Professor at the Defense Acquisition University summarizes the current philosophy in manufacturing regarding variability reduction:

“Modern engineering design, manufacturing engineering, and quality assurance embrace **variability reduction** as a primary means of improving product performance and reducing product defects.”

“Variation creates numerous problems. If we assume our performance and manufacturing specifications have been established correctly, any deviation from the target goal will result in degraded system performance and/or defective components. Variance increases unpredictability in product performance and in the quality and throughput of the factory.” (Motely, 2005).

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In the highway construction arena, variability of materials and construction (M&C) factors such as layer thickness, alignment of dowel bars and tie bars, concrete strength and modulus, initial smoothness, and many others have long been believed to have a significant effect of pavement performance. Variability of M&C factors guarantee that there will be areas along the pavement that are “weak” compared to other sections of “average” or “above average” structural and durability capacity. The weak areas will fail before the average or above average capacity.

For example, NCHRP Project 1-31 (Smith, et al. 1997) established that initial pavement smoothness had a significant effect on future pavement smoothness for both new HMA and JPCP pavements as well as overlays. Unit sections along JPCP (e.g. units of 0.1 to 1.0 miles in length) that were built rougher initially, continued to exhibit a rougher surface for many years into the future. Figure 1 shows 1-mile units along I-55 CRCP in Illinois that varied in initial roughness from 48 to 70 in/mile within a four mile stretch. After 16 years, a range of 70 to 133 in/mile existed in the same order. Further results from the project showed that added pavement life was obtained when increased levels of initial smoothness was attained.

Thus, variability along the project creates “units” that are rougher and these will stay rougher over many future years. These rougher sections would contribute to localized maintenance and to overall project roughness which would shorten the time to rehabilitation based on limiting roughness criteria. For example, pavement at MP 197 will reach 140 in/mile at about 18 years while the other three sections will exceed that time period by many years of additional service.

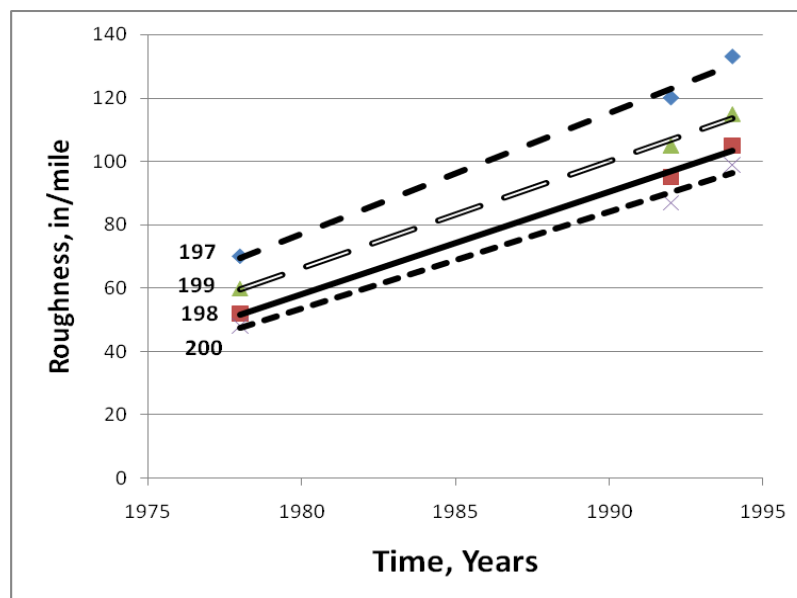


Figure 1. Roughness measured over four miles along Illinois I-55, MP 197 to 201, showing impact of initial smoothness at construction in 1978 on future smoothness. (Smith, et al. 1997)

If performance is affected by variability, then maintenance and rehabilitation needs and timing and overall life cycle costs are also be affected. Despite the widespread belief that variability causes significant performance degradation and cost increases, little direct evidence exists relating variation of materials and construction (M&C) factors directly to variation in

performance. This knowledge is critical to establishing the costs and benefits for variation reduction efforts.

Key questions: Is variability reduction worth the effort in highway construction? Will the costs associated with achieving a reduction in variation be exceeded by the benefits of longer life pavement, reduction in early failures, reduction in maintenance and rehabilitation costs, and reduction in overall life cycle costs (LCC)? And how much does variation need to be reduced to accomplish a significant improvement in performance and reduction in life cycle costs? This paper presents a small portion of a study that addressed all of these issues. (Darter, et al. 2009)

Types of Variability and the Impact on Performance

Variability associated with highway construction projects is illustrated in this section to make the case that it exists and has a profound effect on pavement life.

Survival of Pavements. Survival curves of “families” of pavement sections are one way to show the dramatic impact of variation on performance. Figure 2 shows three survival curves (for 8, 9 and 10-in thick CRCP in Illinois. These curves represent the results of hundreds of projects constructed on the Interstate highway system from the 1960’s through the 1980’s all built to the same specifications for materials and designed with the same design procedure. The horizontal scale is truck traffic in ESALs and the vertical scale is the percentage of these projects that have been overlaid or reconstructed.

8-in CRCP projects show an average load carrying capacity of 15 million ESALS but a range from 2 to 35 million. The 9-in and 10-in CRCP show similar ranges of performance. Why such a wide range in life for similarly designed and constructed pavements with the same specifications and designs? Several sources of variation were the cause of this wide range in life, including layer thickness, concrete strength, foundation support, reinforcement depth differences, construction equipment changes, durability of concrete, and so on.

While variability exists on every construction project and has been acknowledged as a major concern in highway materials and construction, very little research and study has been done to accomplish the following:

1. Collect and document the appropriate measures of variation for M&C factors.
2. Quantifying the impact of this variability on pavement performance.

This section summarizes some of the available data and what is known but still needs to be better understood before the impact of variability on performance can be determined. This section provides the fundamental theory and concepts for properly analyzing the impact of variation of M&C factors on pavement performance. This fundamental approach is then demonstrated for concrete pavement performance and service life. The impact on life cycle costs are provided in a report by Darter, et al. 2009).

Survival CRCP Illinois

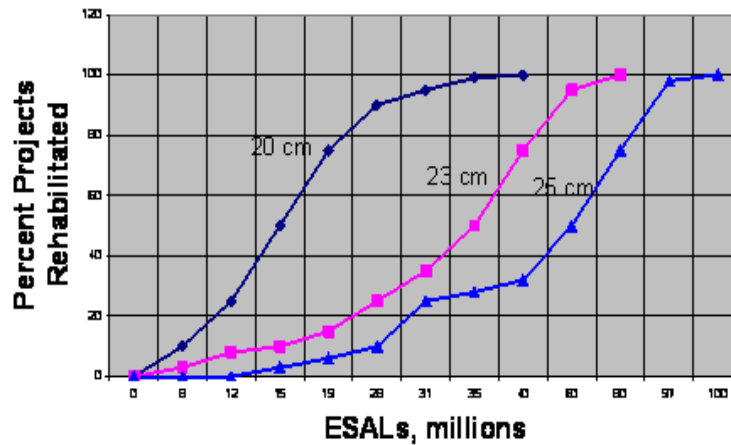


Figure 2. Survival curves for CRCP in Illinois showing variation in pavement life.
(note: each curve represents from 50 to 200 projects) (Gharaibeh, 1999)

Examples of Impact of Variability on Performance. Concrete pavements develop fatigue cracking along the traffic lane over time and traffic. The weakest fatigue locations exhibit this failure first. These areas exhibit material properties, thicknesses, or support that result in the greatest fatigue damage, that show fatigue cracking first. An example of variability “along the project” can be observed in the photos in Figure 3 which shows a view of the highway with no repairs in the right truck lane (left) and the same project down the road a mile or so with many repairs in the truck lane. There are many projects similar to this one where along the project variation can cause significant performance differences.



Figure 3. Photo of JPCP project on I-10 in California showing on left no cracks or repairs in outside truck lane, and on right just down the highway extensive cracking and repairs.

Figure 4 shows the accumulative amount of full depth repair of CRCP of a section of I-57 in Illinois over a nine year period. The frequency distribution also follows a log normal curve with heavy axle loads which is typical for repeated load fracture. Knowledge of the failure distribution allows prediction of future performance.

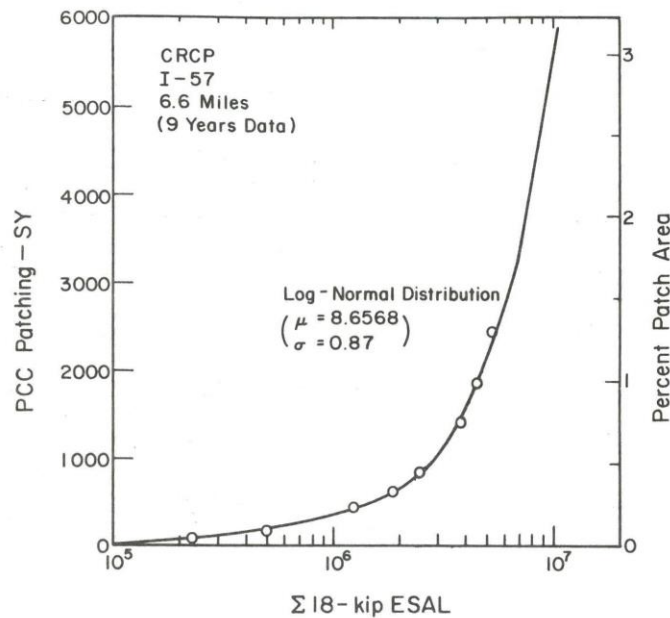


Figure 4. Measured full depth repair quantity version ESALs for a 6.6 mile 8-in CRCP on I-57 in Illinois over a 9 year period. (Maxey, et al. 1979)

Types of Variability of M&C Factors

There are three types of variability associated with construction and of M&C factors as described below.

1. **Variability along the project.** Examples include PCC layer thickness, flexural strength of PCC, dowel bar alignment, and initial smoothness. (Darter 1973) Variations like these are commonly determined from cores or NDT that represent “point to point” variation along a traffic lane in the project. The ranges in M&C factor point to point variations are significant and these would certainly show differences in load carry capacity along the project where the “weakest” point would fail in fatigue first over time and traffic. Variation along the project can also be considered as an aggregation of points into a “unit” of length. Smoothness is typically measured over a 0.1 mile length of traffic lane and is referred to as “unit” variation. There would also be “unit” variation of such M&C factors as mean PCC thickness and mean PCC strength. This unit mean variation would be less than the point to point variation as it would be the variation of mean thickness or strength from unit to unit along the project. (Darter, et al. 2009)
2. **Variability between mean project as-designed/specified and mean project as-constructed.** An example includes the difference between mean project PCC thickness as-designed and mean PCC thickness as-constructed. Another example includes the difference between mean project IRI as-specified and as-designed and mean IRI as-constructed. While this variation is important, it is not directly considered in this analysis since it does not relate specifically to along the project variability which is of top interest in this paper. (Darter 1973)

3. **Variability from testing or measurement.** This includes repeated lab or field testing of replicate samples or replicate points on the pavement. Examples include testing replicate concrete cylinders and repeated runs to measure profile and convert it to IRI. It is obvious that testing variability does not affect performance of the actual pavement. Thus, it must be subtracted from the total along the project variability.

Additional Details on Variability along the Project. This paper focuses on variation that occurs “along the project” of M&C factors. The impact of this type of variation on performance can be considered on a “point to point” level along the pavement and on a “unit to unit” level along the pavement.

1. **Point to point variability:** As this implies, this type of along the project variability is illustrated by thickness variation from cores measured along the project. This variation can be quite high. (Darter, et al, 2009)
2. **Unit to unit variability:** Unit to unit variation along a project is illustrated in figures 5, 6, and 7 for 0.1-mile long units along a JPCP construction project on I-39/90/94 in Wisconsin. Here the units mean thickness, strength, and profile index along the project are illustrated. As can be observed, even though these represent the mean values of a 0.1-mile unit of pavement, there is still considerable variation along the project.

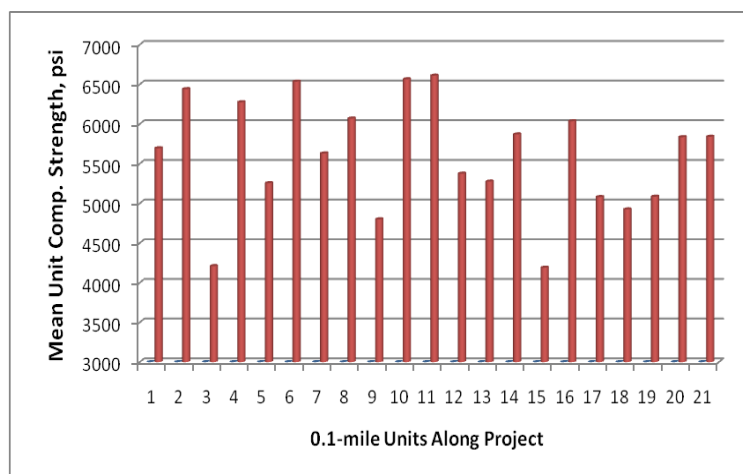


Figure 5. Unit (0.1-mile) mean compressive strength variation along Wisconsin I-39/90/94 project (Mean = 5600 psi, CV = 12 percent). (Rao, et al. 2007)

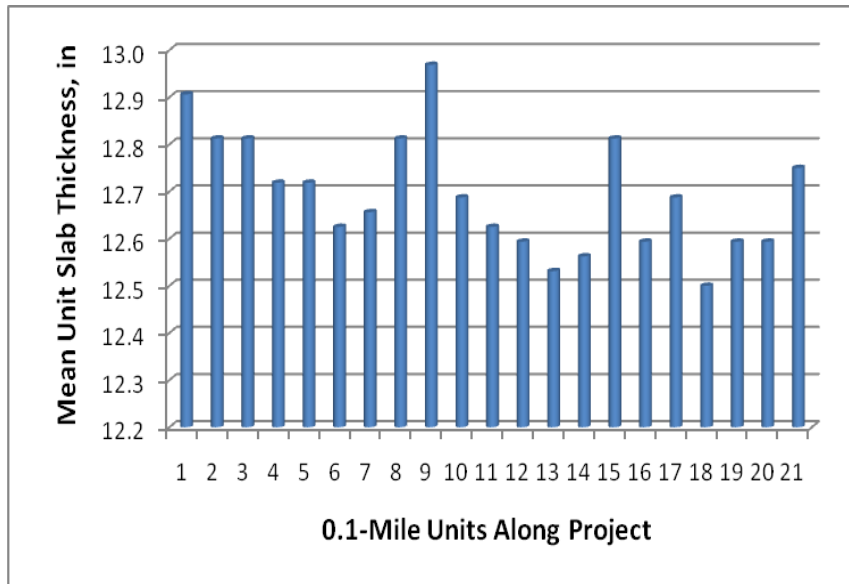


Figure 6. Unit (0.1-mile) means slab thickness along Wisconsin I-39/90/94 project (Mean = 12.7-in, CV = 1 percent). (Rao, et al. 2007)

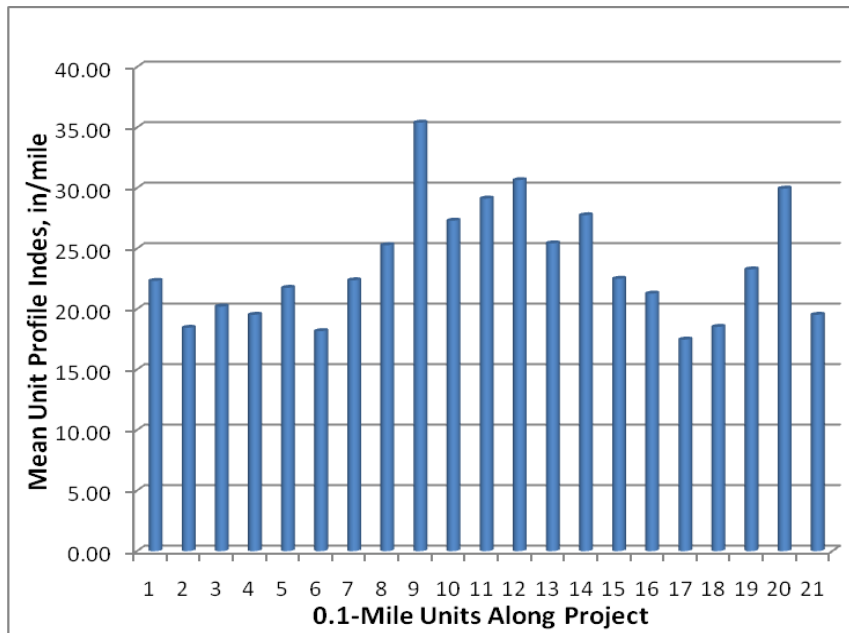


Figure 7. Unit (0.1-mile) means profile index along Wisconsin I-39/90/94 project (Mean = 23.6 in/mile, CV = 21percent). (Rao, et al. 2007)

Relationship of Point to Point and Unit to Unit Variation. Determining the effect of variation of M&C factors on performance should examine both “point to point” and “unit to unit” variation. For example, if point to point variation is high, unit to unit variation should also be high. Point to point variation will result in specific locations in a traffic lane where the pavement will exhibit “weak” M&C factors, such as a thin PCC layer and low strength. The higher the point to point variation along a project the higher the amount of early failure over time and traffic. High point to point variation along a project leads to higher unit to unit variation along the same highway.

Simulation of Variation to Estimate Impact on Performance. Pavement performance is complex and thus cannot easily be predicted. The distress and IRI models in the AASHTO MEPDG provide the best available models for predicting performance along a project. The MEPDG was calibrated to field performance using “unit” sections from LTPP which were approximately 0.1-mile in length. Thus, the prediction of distress and IRI from the MEPDG models is actually predicting the results for a “unit” of pavement.

This paper will utilize simulation to show the relative impact of variation of M&C factors along the project to performance of the project. Obviously, the proper variances and distributions must be used that actually exist along the project to show the impact they have on performance along the project. Many studies have conducted simulation and its supposed impact on performance. However, they have not used the proper “unit” to “unit” variances and distributions to demonstrate the true impact. Obtaining the proper variances is THE key activity before the impact of variation on performance can be determined. See details in Darter, et al. 2009.

Example of Impact of Variation of M&C Factors on Performance

An example is provided using actual variability data from Wisconsin for a JPCP. This example shows the following:

- Obtained extensive project M&C variability data from Wisconsin for initial IRI, slab thickness, and PCC strength on a “unit” basis, to estimate variance between “units”.
- Conducted a simulation experiment for an actual Wisconsin highway to demonstrate the impact of M&C variation on “unit” performance variability in terms of cracking, IRI, and faulting.
- Provided a sensitivity analysis that changes the level of variation from that typical in Wisconsin on actual projects to lower values to demonstrate the impact on pavement service life.

The specific highway is described as follows. Some feature designs were changed to provide a longer life project to use as an example (e.g., dowels were added).

- Wisconsin US 18 (17 miles from Lone Rock, WI)
- Constructed 1989
- 10-in JPCP (dowels included)
- Aggregate base (low fines, 2.3%)
- Subgrade A-1-b

- Joint spacing uniform 15-ft.

Three M&C factors will be included in this example simulation:

1. Initial smoothness, as measured by IRI.
2. Concrete slab thickness
3. Concrete compressive strength

Initial Smoothness

An estimate of the variance of initial smoothness was calculated from Wisconsin QA data based on eight projects. These data were divided into the following components for analysis:

- 8 projects ranging in total length from 1.5 to 10 miles.
- “Units” for measurement of IRI were 0.1-mile long by one traffic lane. There were a total of 1104 “units” of profile measurement.
- Inside and outside traffic lane were measured.
- Inner and outer wheel paths were measured. These values were averaged to obtain a single value per traffic lane which is how the MEPDG/LTPP data were defined and used.

An analysis of variance was conducted using the massive amount of initial construction IRI data from these 8 projects as shown in table 1. The analysis of variance breaks out the components of variation which include projects, units within project (0.1 mile length), lanes, and testing error. The mean square represents the variance of IRI between units. This variance is 163 in units of in/mile squared. The square root of 163 is 13 in/mile represents the component of variance associated with IRI between “units” 0.1-mile long along the 8 projects.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Statistic	Comment
Projects	7	36917	5274	83.71 <0.0001	Highly Significant
Units	544	88470	163	2.58 <0.0001	Highly Significant
Lane	1	25	25	0.40 0.5259	Not Significant
Error	551	34715	63		
Corrected Total	1103	160129			

Table 1. Analysis of variance of initial IRI conducted over 8 Wisconsin projects to determine the component of variance associated with “unit to unit” along the project.

A project 6 miles in length was used in the example analysis. This project would have 60 “units” of 0.1-mile long. Thus, 60 initial IRI values were simulated to represent the typical unit to unit variation in initial IRI. A plot of these values is shown in figure 8.

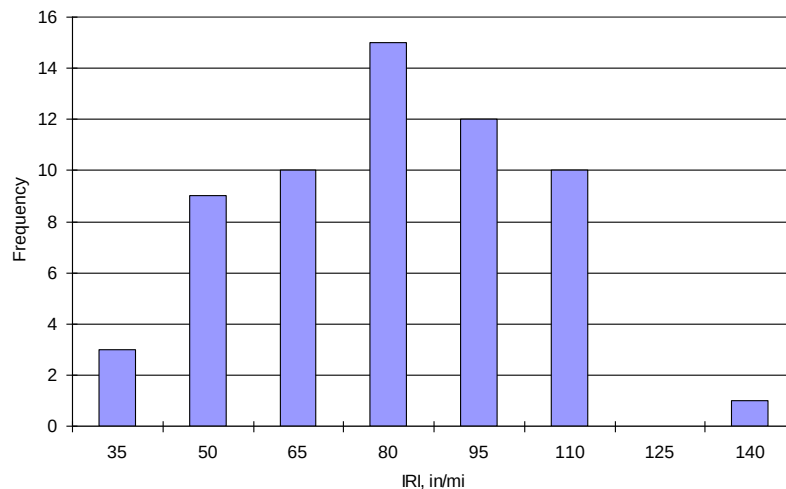


Figure 8. Variation of initial IRI representing 60 units along the 6-mile project.
(Mean = 70 in/mile, standard deviation = 13 in/mile)

Concrete Slab Thickness

An estimate of the variance of slab thickness was calculated from Wisconsin QA data based on 6 projects. Thickness was measured in the plastic concrete using a probe with a metal base plate. These data were divided into the following components for analysis:

- 6 projects ranging in total length from 1.5 to 10 miles.
- “Units” for measurement of slab thickness were 500-ft long by one traffic lane. There were a total of 388 “units” of thickness measurement.
- Inside and outside traffic lane were measured.
- 4 replicates within each lane were measured.

An analysis of variance was conducted using the massive amount of initial construction concrete slab thickness from 6 Wisconsin projects. The analysis of variance (similar to IRI approach) breaks out the components of variation which include projects, units within project (0.1 mile length), lanes, and testing error. The mean square represents the variance of thickness between units. This variance is 0.19 in squared. The square root of 0.19 is 0.34-in and represents the component of variance associated with slab thickness between “units” 0.1-mile long along the 6 projects.

- Thickness Unit to Unit Variance (minus testing) = $0.19 - 0.09 = 0.10$ in squared.
- Thickness Unit to Unit Standard Deviation = 0.32 in (this will be used in the simulation with a Normal distribution).

A project 6 miles in length was used in the example analysis. This project would have 60 “units” of 0.1-mile long. Thus, 60 mean unit thickness values were simulated to represent the typical unit to unit variation in slab thickness.

Concrete Compressive Strength

An estimate of the variance of concrete strength was calculated from Wisconsin QA data based on 4 projects. Compressive strength was measured at 28-days. These data were divided into the following components for analysis:

- 4 projects ranging in total length from 1.5 to 10 miles.
- 43 lots (essentially daily production)
- 297 “Units” or sublots for measurement of concrete strength were 500-ft long. Unfortunately, strength data for each individual lot were not available, thus, only the mean was available for each subplot or “unit”.
- 2 replicate cylinders within each batch were tested and the mean determined. Data were not available for the individual cylinders, thus, the mean of two were used in the analysis.

An analysis of variance was conducted using the massive amount of initial construction concrete compressive strength from 4 Wisconsin projects. The analysis of variance breaks out the components of variation which include projects, lots (lots were used as units within project for this example), and testing error (similar to that done with IRI). The mean square represents the variance of thickness between units. This variance is 88,447 psi squared. The square root of 88,447 is 297psi and represent the standard deviation associated with mean compressive strength between “units” 0.1-mile long along the 4 projects.

The last component of variance of strength is the testing error. The testing error for strength measured by compressive strength is in the order of a CV of 5 percent. A 4500 psi concrete would have a testing standard deviation of 225 psi. This variance will be subtracted from the other two major components of variance.

- Thickness Unit to Unit Variance (minus testing) = $88,447 - 225^2 = 37,822$.
- Thickness Unit to Unit Standard Deviation = 194 psi (this will be used in the simulation with a Normal distribution).

A project 6 miles in length was used in the example analysis. This project would have 60 “units” of 0.1-mile long. Thus, 60 mean unit mean strength values were simulated to represent the typical unit to unit variation in slab strength.

Simulation of Performance of 6-Mile JPCP

The AASHTO MEPDG models were utilized to predict the performance of the 60 “units” along the 6-mile Wisconsin project. It should be noted that only three M&C factors, initial IRI, slab thickness, and concrete strength are used in the simulation. Several others could also be included if the variances could be estimated (e.g., coefficient of thermal expansion of concrete, equivalent dowel diameter, subgrade support, permanent built in curl/warp temperature gradient).

The MEPDG was run 60 times and each run included a randomly generated initial IRI, slab thickness, and compressive strength (28-day) (note that the E_c was correlated with the strength for each run using the standard ACI equation). Thus, 60 curves of performance output were obtained and analyzed for slab transverse fatigue cracking, joint faulting, and IRI over a 20 year analysis period. Critical values were set at 15 percent slabs cracked, 0.12-in mean joint faulting, and 150 in/mile IRI for estimating pavement life. Various plots were prepared to show and illustrate the results.

- Figure 9 shows that the age of pavement 0.1-mile units when 15 percent cracking is achieved varies from 20 to 90 years. This is very wide range based on the variation of only three M&C factors and shows the significant impact of variation on performance.
- Figure 10 shows that transverse slab cracking at 20-years of age of 0.1-mile units along JPCP project ranges from 2 to nearly 30 percent slabs. This is a very wide range again and shows the significant impact of variation on performance.
- Figure 11 shows that the number of cumulative trucks on 0.1-mile units along JPCP project when 15 percent transverse cracking is reached ranges from 10 to over 70 million. Variation of M&C factors result in a major impact on structural capacity.
- Figure 12 shows that the IRI at 20-years of age of units along JPCP project ranges from 100 to 180 in/mile. Thus, some of the 0.1-mile units along the project would be relatively smooth while some would be very rough after 20 years.

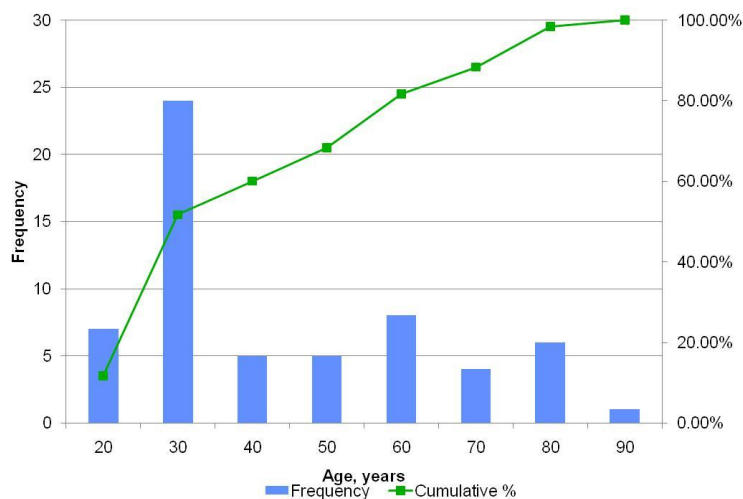


Figure 9. Variation of Age of 0.1-mile units along JPCP project at 15 percent transverse cracking.

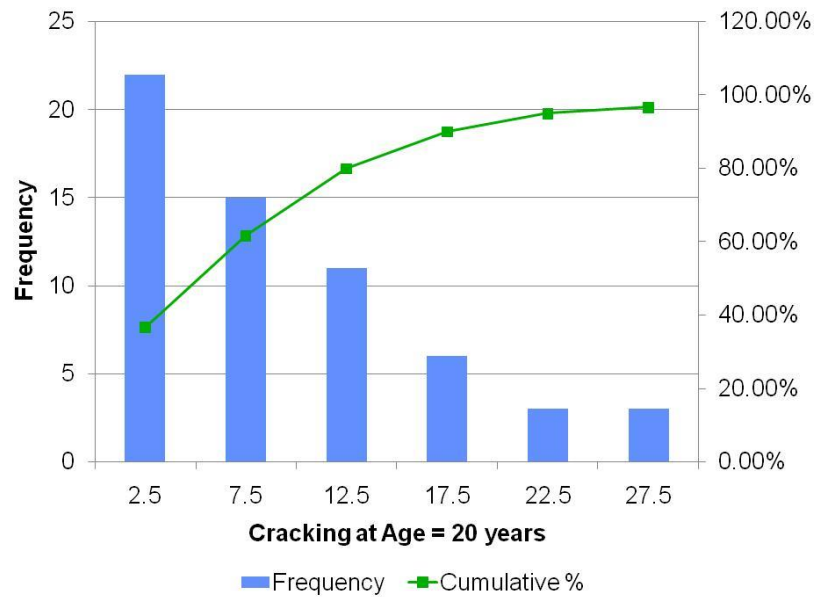


Figure 10. Variation of transverse slab cracking of 0.1-mile units along JPCP project at 20-years.

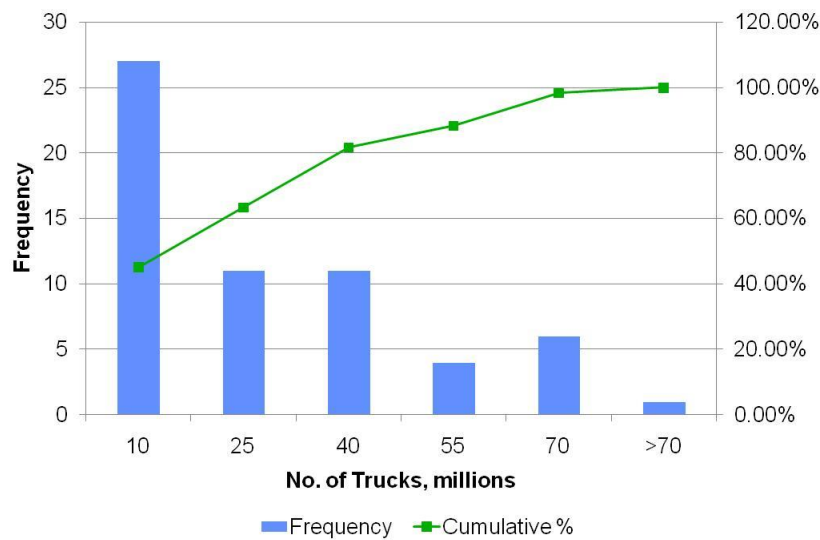


Figure 11. Variation of Number of Cumulative Trucks of 0.1-mile units along JPCP project at 15 percent transverse cracking.

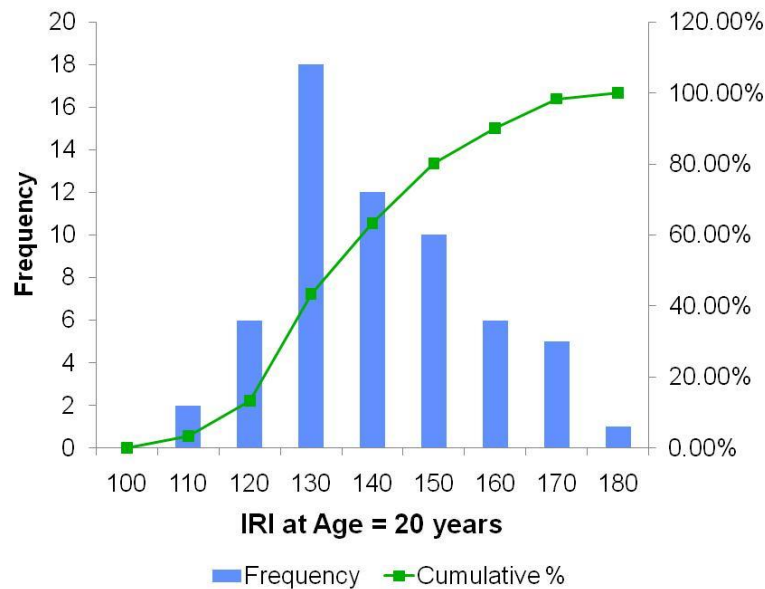


Figure 12. Variation of IRI at 20-years of age of units along JPCP project.

Finally, figure 13 shows the “typical variability” cumulative distribution of percent failure (Cracked slabs > 15 percent) of 0.1-mile units along the 6-mile JPCP project. This plot shows better than any other the impact of “typical variability” of M&C factors on performance. By 20 years over 10 percent of the 0.1-mile units have exceeded the 15 percent cracked slab critical limit where rehabilitation is often performed. The failure curve rapidly accelerates after that point in time until by 30 years over 50 percent failure of 0.1-mile units have occurred. State pavement management system trigger points for rehabilitation is typically about 10 to 20 percent cracked slabs. If the variability of M&C factors could be reduced, these early failures would be reduced as presented in the next section.

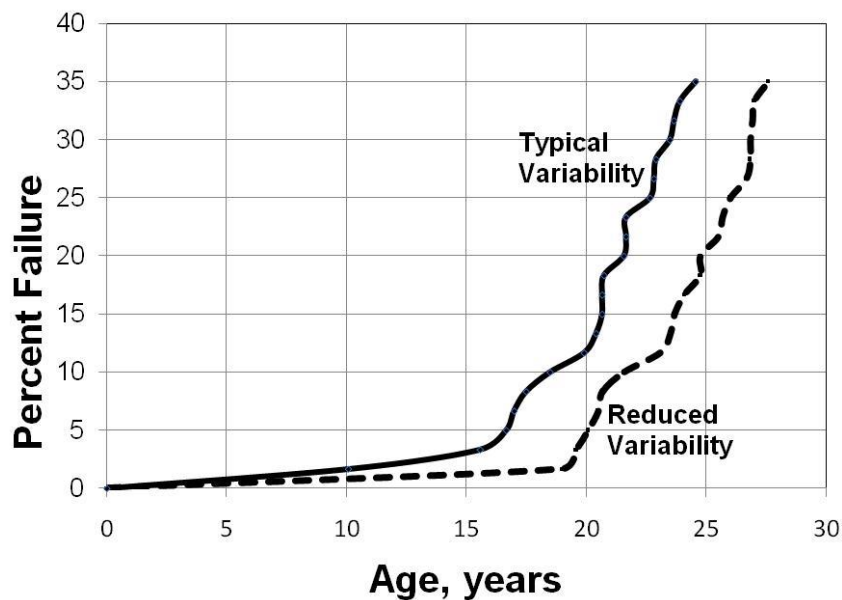


Figure 13. Cumulative distribution of Percent Failure (Cracked slabs > 15 percent) of 0.1-mile units along 6-mile JPCP project.

Reduced Variation Effect

The impact of reduced variation of initial IRI, compressive strength, and slab thickness along the project would be to reduce the amount of early failures over time. The variations of M&C factors used in the simulation were established using substantial data from Wisconsin JPCP projects. If these variations could be reduced, how would it impact performance? A new simulation was run with standard deviations at ½ of the “typical” values found in the analysis of variance of Wisconsin data. These values are as follows:

- Initial IRI: Std. Dev. = **6.2 in/mile Vs 13.4 in/mile.**
- Concrete strength: Standard Deviation = **88 Vs 171-psi.**
- Slab Thickness: Standard Deviation = **0.15 Vs 0.32-in.**

The simulation with reduced variability was conducted in exactly the same way as it was for typical variability. The outputs show reduced failures for slab cracking, joint faulting, and IRI. The results were summarized in the “reduced variability” survival curve in figure 13. The reduced variability performance curve has shifted to the right by several years resulting in reduced failures from cracking and thus longer pavement life.

Reduced variability of three M&C inputs resulted in extended pavement life until critical level of cracking occurred.

- **Typical variation:** 17 years to reach 10 percent cracked slabs.
- **Reduced variation:** 22 years to reach 10 percent cracked slabs.

- **29 percent increase in project life for this example based on slab transverse cracking.**

A life increase of 29 percent represents a very significant increase. This would translate to reduced lane closures, reduced slab cracking replacement, and reduced roughness over the life of the pavement. This result would likely translate into a significant reduction in life cycle costs of the project.

Summary of JPCP Example Results

This example provided a simulation using variances for only three M&C factors obtained from large amounts of historical data from a major highway project in the State of Wisconsin. The following results were determined from the simulation of 60 lots, or 6-miles along the project.

1. Variations of M&C strength, thickness, and initial IRI factors have significant effect on service life along a typical JPCP project resulting in early failures. For example, the percent of slabs cracked at 20-years ranged from 2.5 to nearly 30 percent. The number of trucks that each of these “units” could carry before reaching 15 percent cracked slabs ranged from 10 to over 70 million.
2. Early failures impact performance, maintenance cost, and could result in early rehabilitation, both increasing life-cycle costs of pavement.
3. Reduction in variation of M&C factors of 50 percent resulted in a 29 percent increase in pavement life.
4. Life-cycle analyses could be conducted using these results to demonstrate the impact over the design life. (see Darter, et al. 2009)

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